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Lunar Polar
Science & Exploration

Characterizing Luna Incognita

Scientific & Exploration Potential of the Lunar Poles

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Imperial College London
Lunar Geotechnical Institute
Mount Holyoke College
NASA Glenn
NASA Marshall
NASA Ames
Smithsonian Institution
Space Telescope Science Institute
US Army Cold Regions Research & Engineering
University of Alabama
University of Toronto
University of Washington
University College London
United States Geological Survey

NASA LUNAR SCIENCE INSTITUTE

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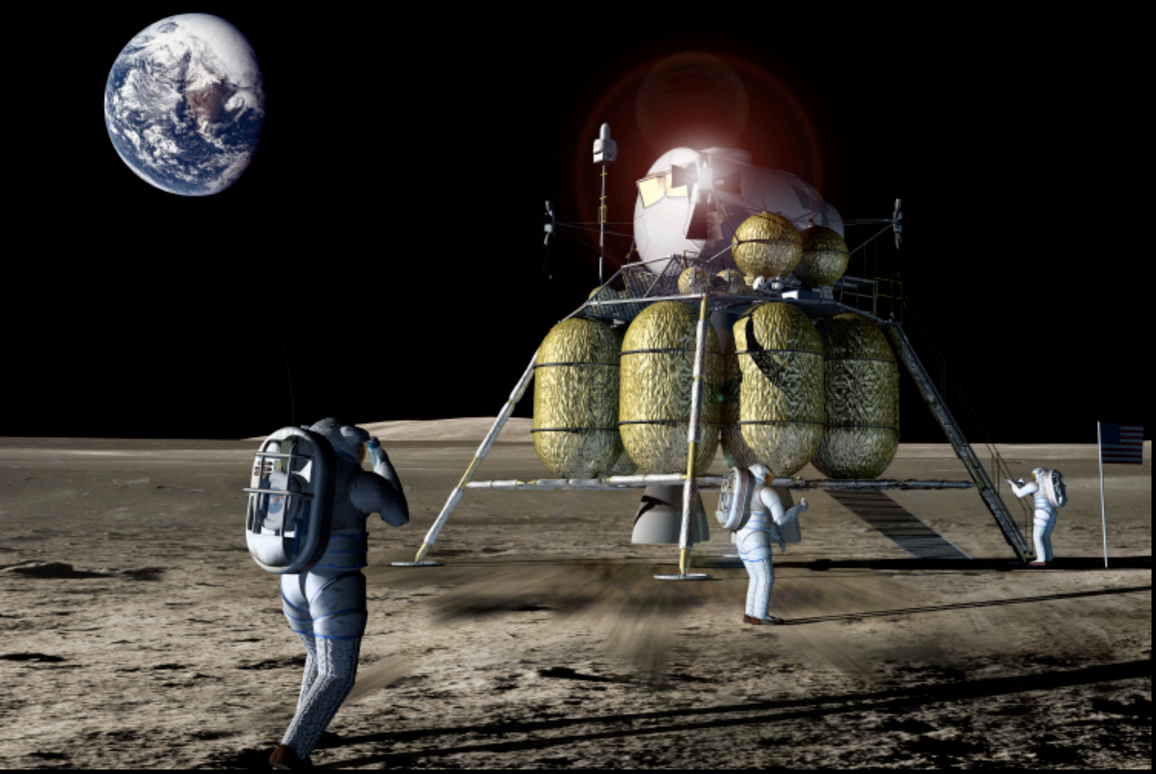
The Lunar Poles: An Ideal Site for Scientific Exploration?



Yes!

1. It's the Moon

2. The Poles Offer a Unique Exploration Opportunity

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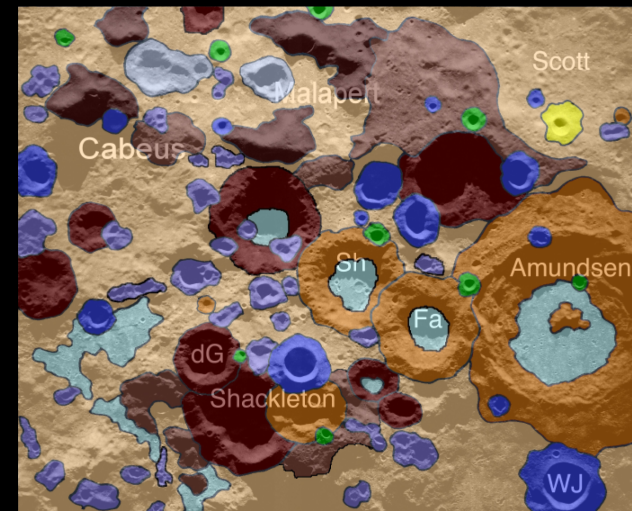
Exploring Luna Incognita

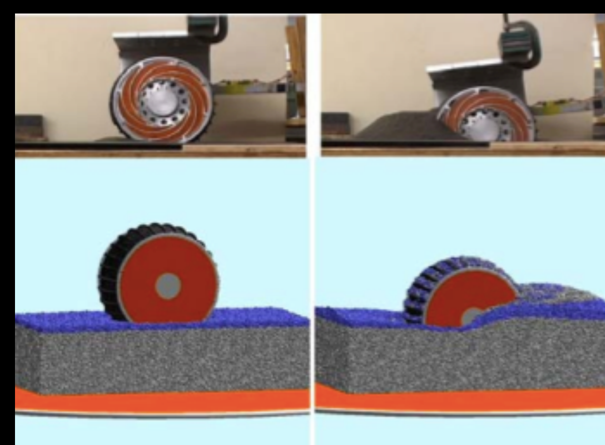


- Lunar Polar Environment
  - Polar geology
  - Illumination & thermal studies
  - Volatile transport modeling
  - Volatile laboratory studies

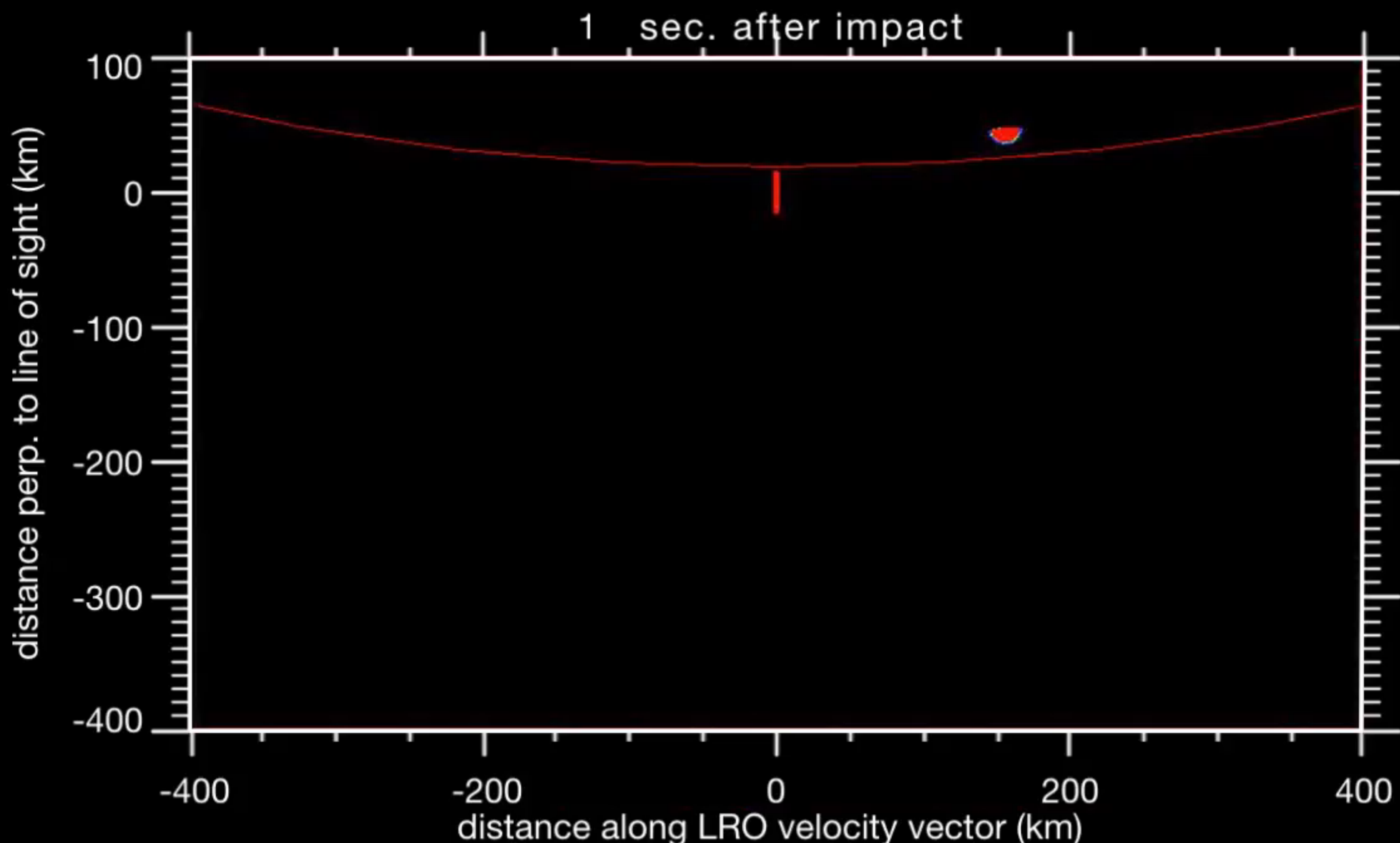
- Surface characterization

- Surface science, instrumentation & operations
  - Surface mobility & excavation
  - Ground penetrating radar
  - Surface neutron instrumentation
  - Earth observation

- EPO



Simulations of LCROSS Plume

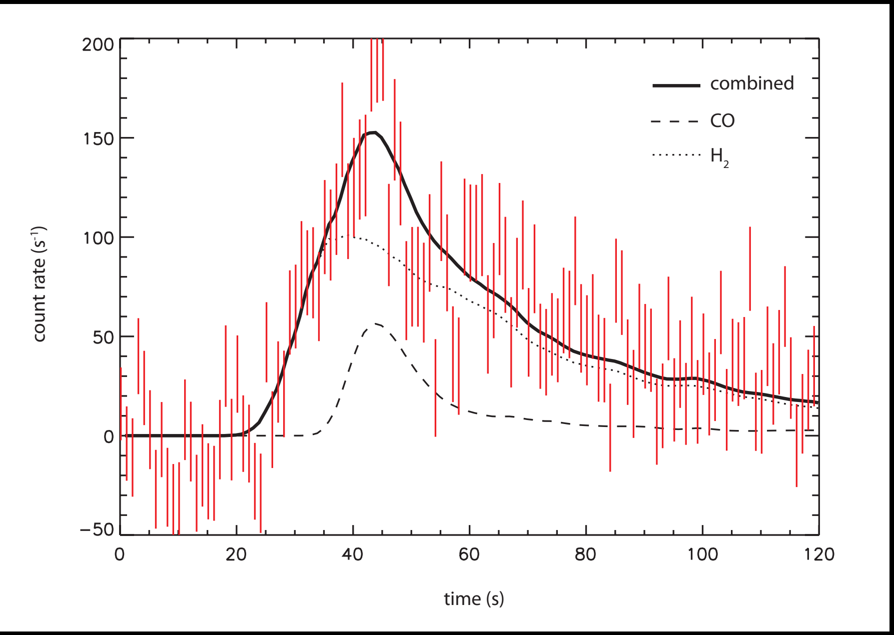


Dana Hurley, *JHU/APL*

LCROSS-Simulated Time Series

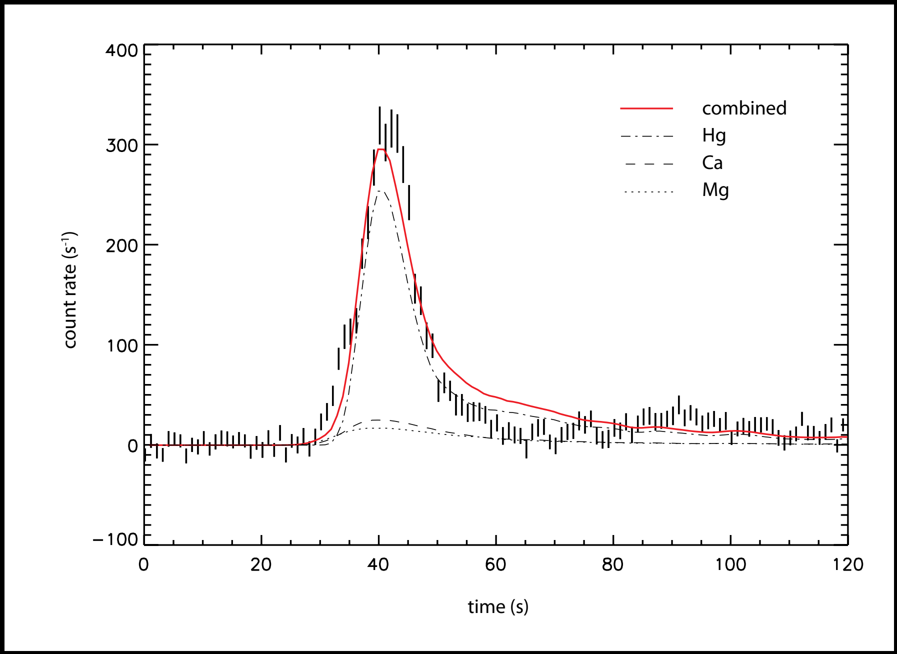
H_2 and CO, 130-165 nm

- Fit with a 3.25 km/s non-thermal (bulk) velocity and T=500K



Hg, Mg, and Ca, 170-180 nm

- Fit with a 3.7 km/s non-thermal (bulk) velocity and 2000 K (although T is not well constrained)



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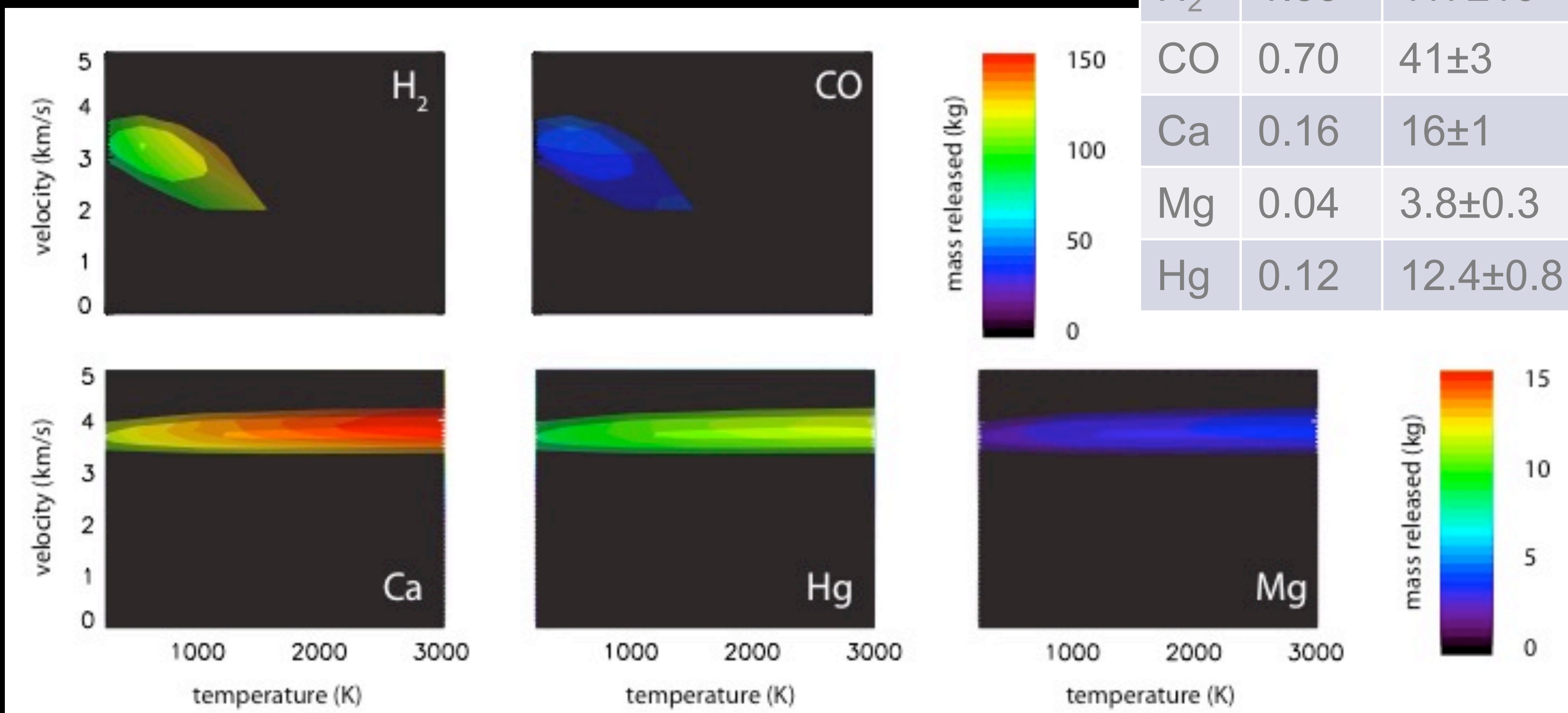
Total Mass of Vapor Released

- The modeled mass released of each constituent observed by LAMP to match the observations

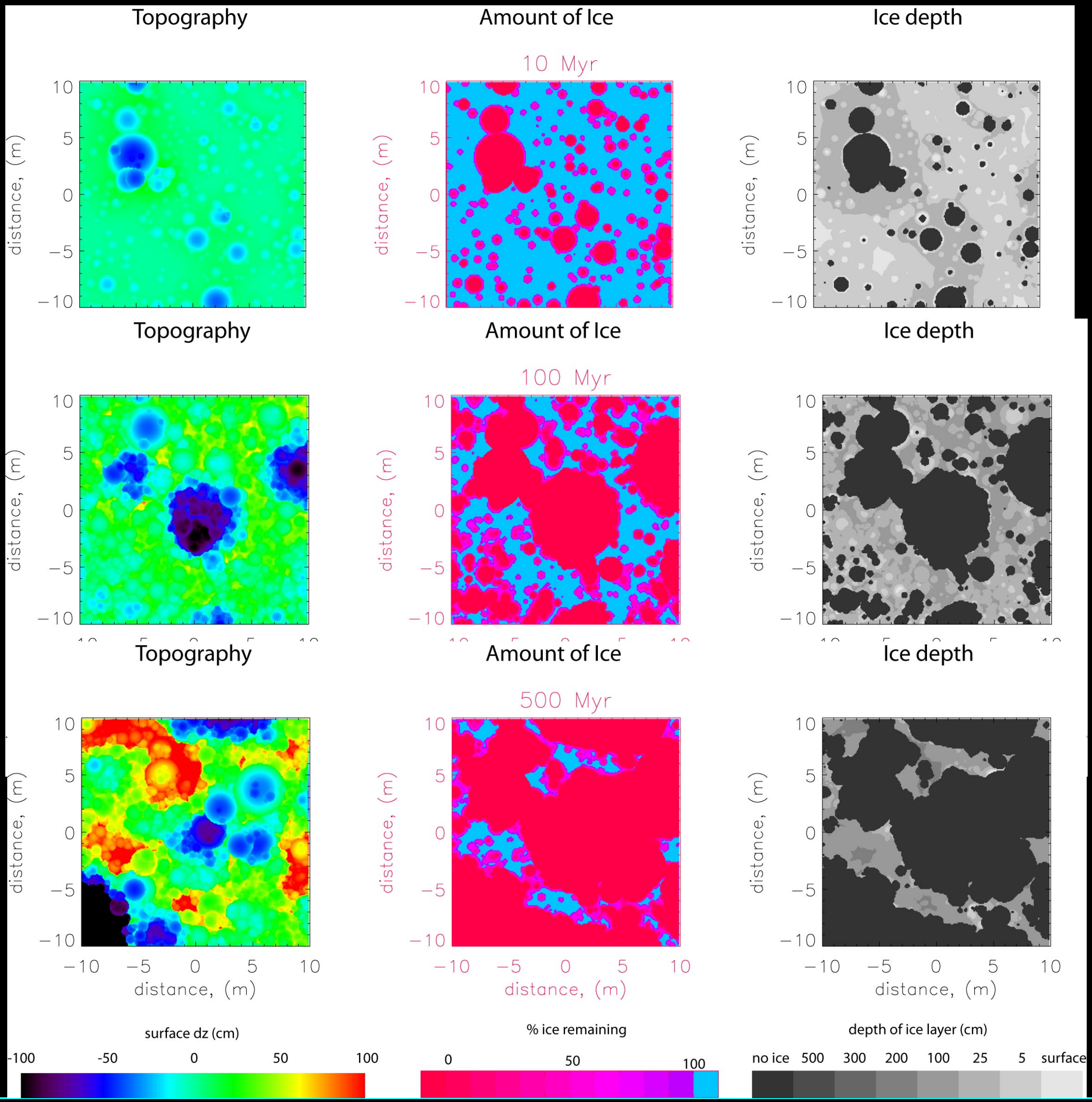
Species	Observed (kg)	Mass released (kg)
H_2	1.33	117±16
CO	0.70	41±3
Ca	0.16	16±1
Mg	0.04	3.8±0.3
Hg	0.12	12.4±0.8



ISRU Mission Definition

- To utilize volatiles as a resource on the Moon, one needs to identify where to find them and how to access them
- Missions to test ISRU will need to plan for mobility and subsurface access
  - Develop feasible architectural scenarios for resource development
- Our work enables trade studies:
  - How deep to drill?
  - How far to rove?

Predicting Volatile Heterogeneity



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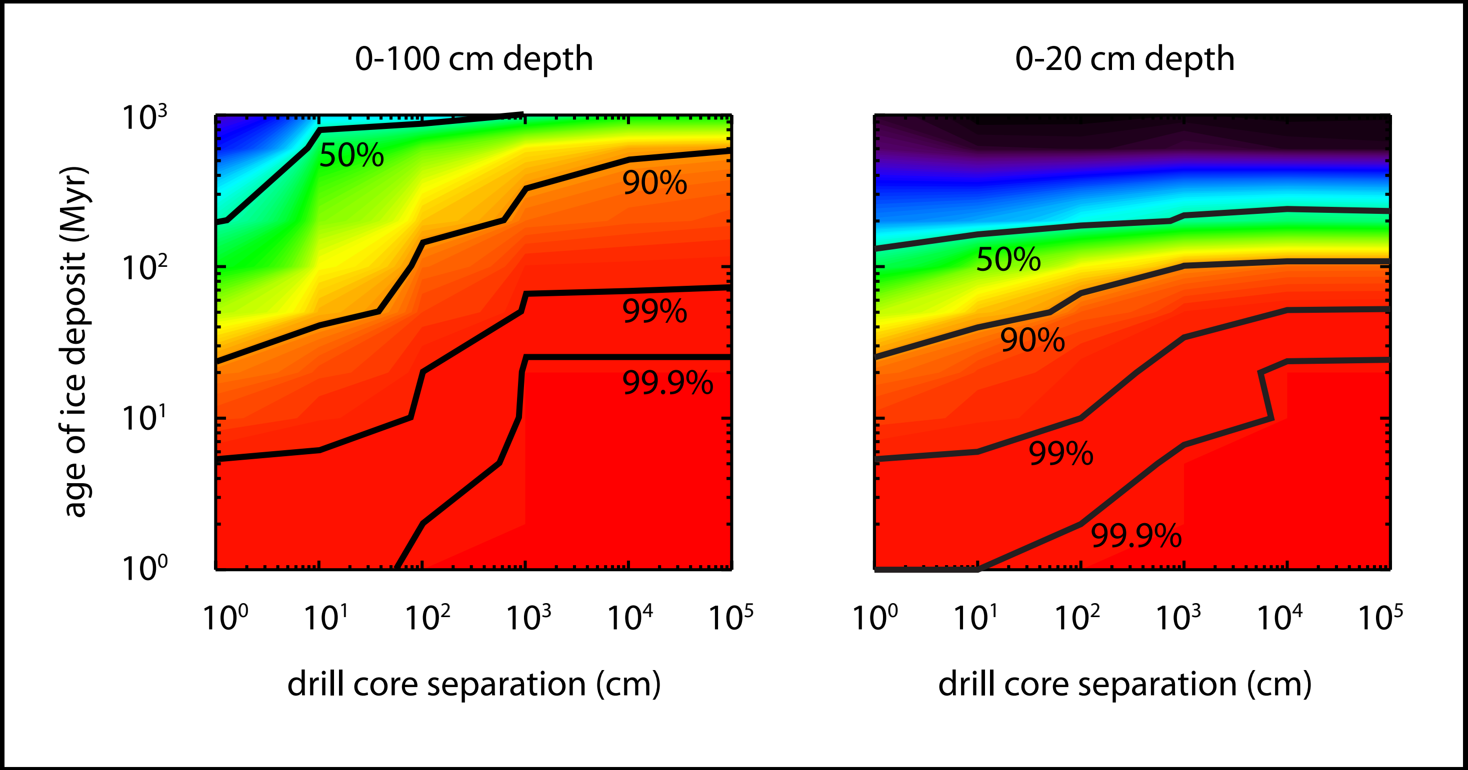
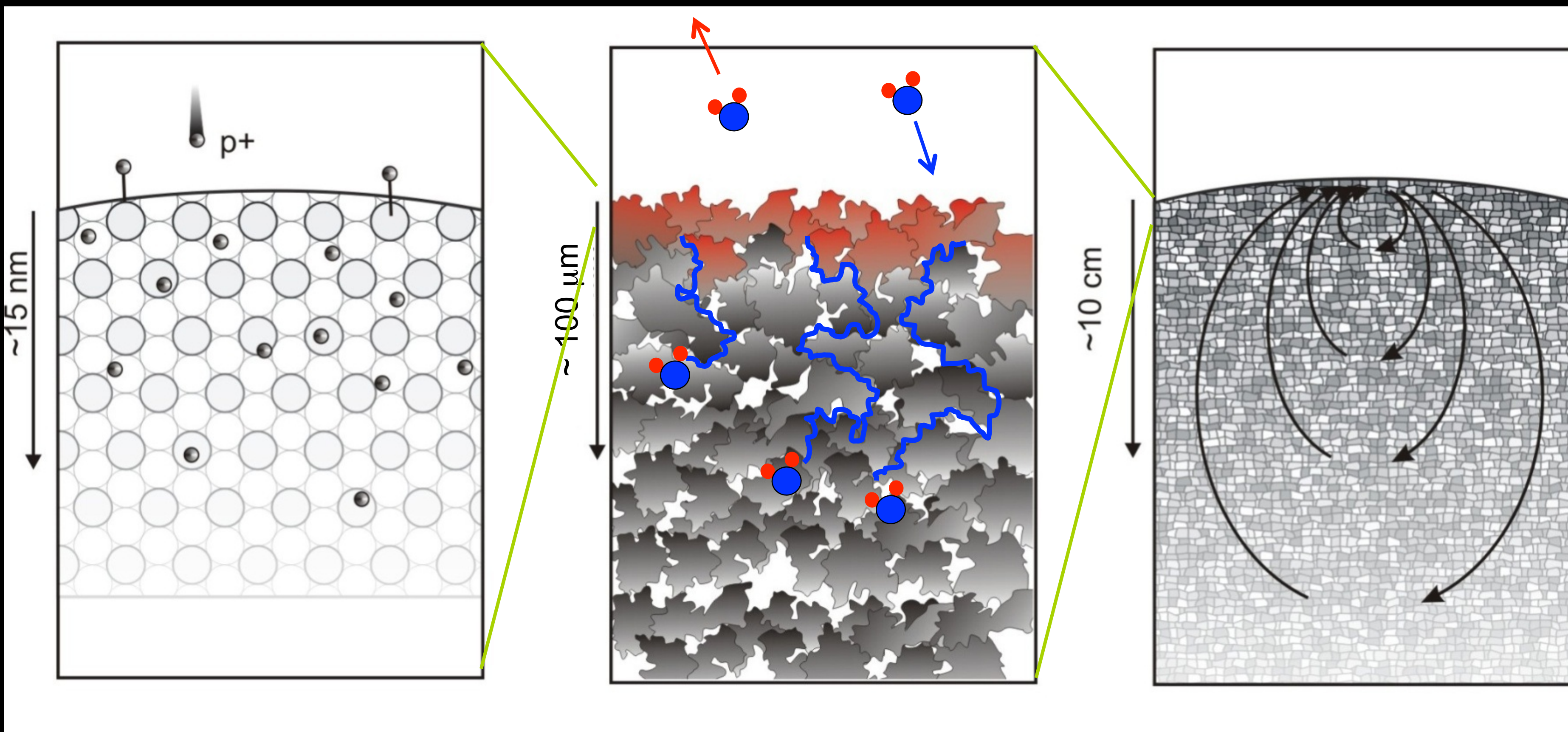
Predicting Volatile Heterogeneity

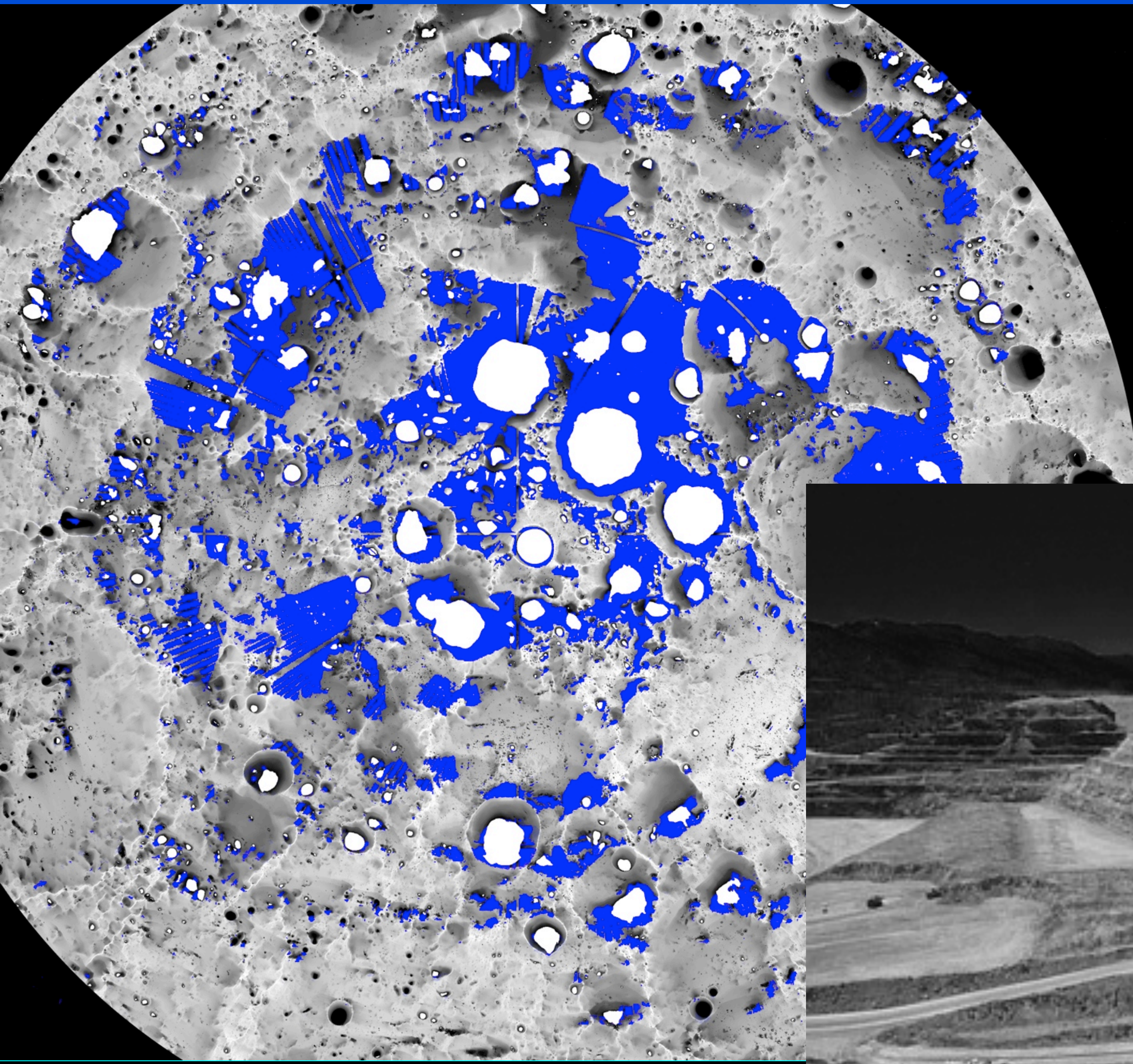
- Chances of finding PSR volatiles as a function of age of volatile deposit, drill depth, and roving distance



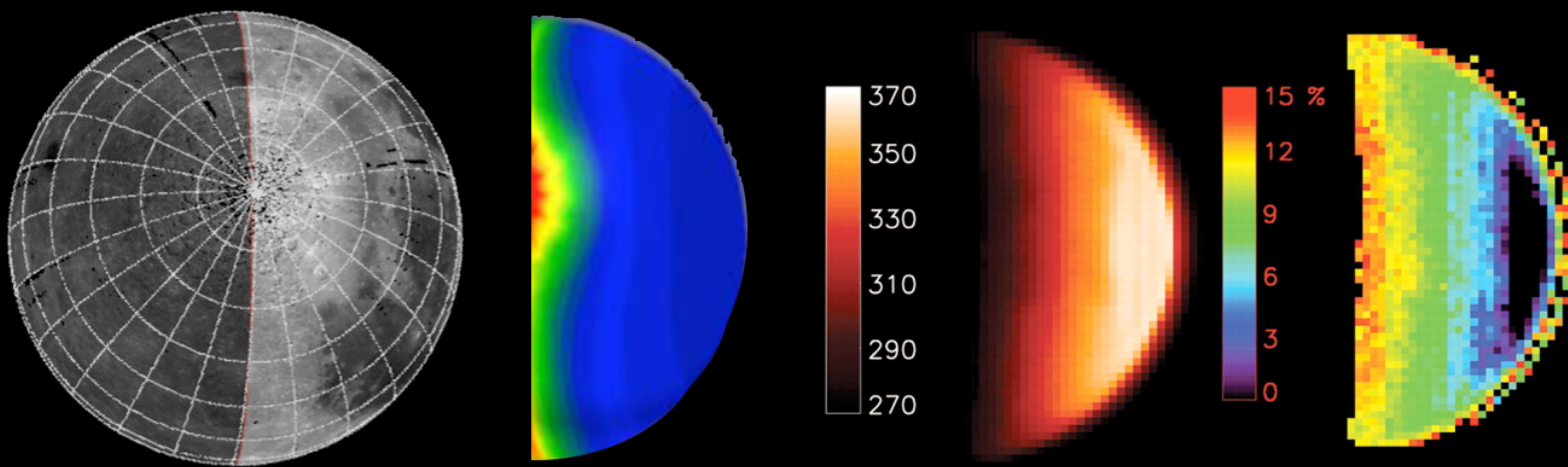
Modeling/Lab Analyses of OH/H_2O



Water and ice on the Moon…



Models of solar wind formation and loss of OH compared to observations.



Albedo Map Night/Day

Modeled OH distribution

Observed Temperature

Observed OH distribution

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Lunar Regolith Mobility and Excavation Modeling

J.B. Johnson[1], J. Agui[2], C. Creager[2] M.A. Hopkins[3], M. Knuth[3], A. Kulchitsky[1] H. Oravec[2], A. Wilkinson[2], K. Zacny[4]

[1]U. of Alaska-Fairbanks, [2]NASA Glen Research Center [3]USA-ERDC-CRREL, [4]Honeybee Robotics

- The problem - The effects of different gravity, soil types and physical processes on the Moon, asteroids, and other planets make it impossible to accurately predict machine performance from Earth-based tests alone or from traditional models

- The goal - To develop a physical discrete element method (DEM) model that non-DEM-specialists can use to solve a variety problems in space science and engineering related to the moon (e.g., excavation and mobility, crater wall weathering, volatile migration in regolith, asteroids and small bodies, and planetary surfaces)

- A physical DEM incorporates micro-scale physically based process algorithms that produce emergent macro-scale behavior – that is, a virtual experiment

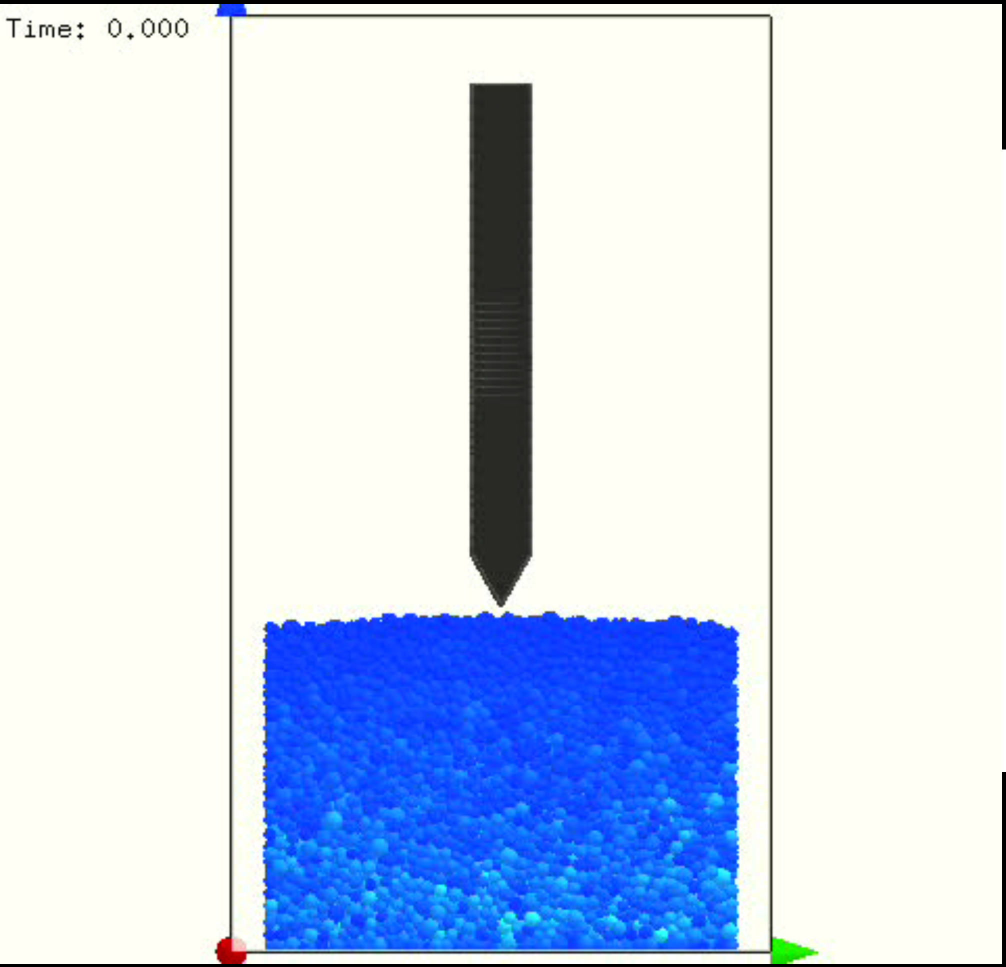
Approach

- Used CRREL DEM modeling expertise to jump-start and facilitate development of the NLSI (UAF) *user-oriented* research physical DEM model Controllable Objects Unbounded Particles interactions (COUPi)
- Used physical experiments to guide model development and validate simulation accuracy
  - Mobility (NASA GRC and Cornell Univ.)
  - Excavation - static & percussive (Honeybee Robotics; NASA GRC)
  - Geotech. Properties - micromechanical, tri-axial & penetrometer (NASA GRC; Honeybee Robotics; USACE CRREL; Other.
- Apply COUPi to simulate specific tests to demonstrate accuracy and improve modeling approaches
  - Percussive and static excavation
  - Mars exploration wheel digging and in-situ (on mars) wheel scuff
  - Cone penetration soil strength tests

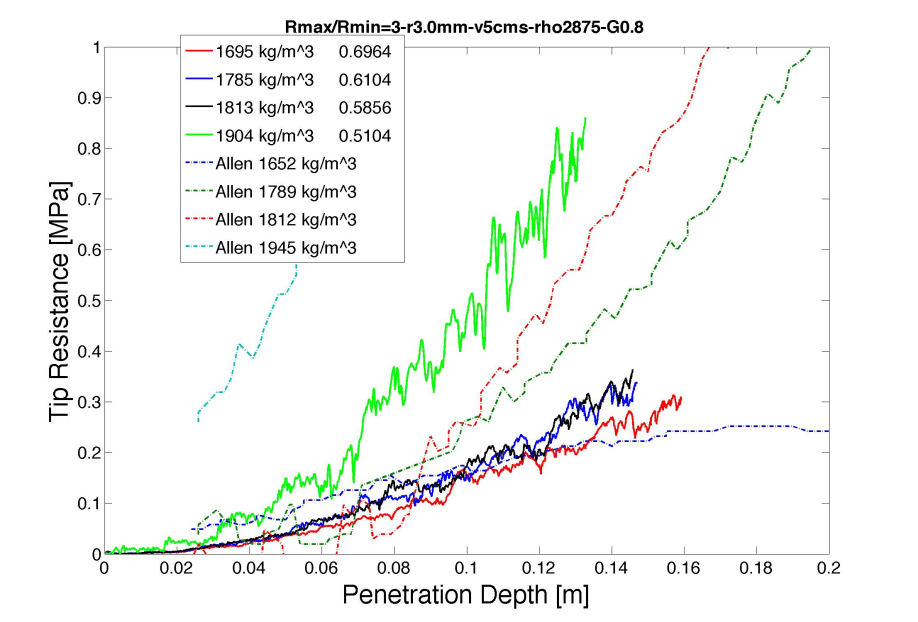
Accomplishments (1/2)

- Demonstrated that DEM modeling can accurately simulate important excavation and mobility problems that cannot be solve in other ways
  - MER wheel digging and scuffs
  - Percussive and static excavation
  - Tri-axial geotechnical strength tests
  - Cone penetrometer strength tests
- Modified the multi-processor COUPi DEM by
  - Cone penetrometer strength tests
  - Tri-axial geotechnical strength tests
  - Densification of log-normal sized particles
  - Asteroid formation for dispersed objects (to demonstrate self-gravity effects)
  - Asteroid capture simulation (to demonstrate the ability to introduce control function - i.e., for the capture rockets.
  - Import CAD drawing the MER rover wheel for simulation

Cone Penetrometer Test (CPT)



CPT simulation using tri-sphere particles



Penetrometer tip resistance
Versus penetration depth for
Three different densities

Accomplishments (2/2)

- Developed extensive experimental data set on mobility and excavation
  - Percussive and static excavation (identified cause of reduced regolith strength due to percussive excavation)
  - Tri-axial geotechnical strength tests
  - Cone penetrometer strength tests
  - Created a numeric code to predict the approximate the reaction force for percussive excavation.
  - MER wheel digging and scuffs

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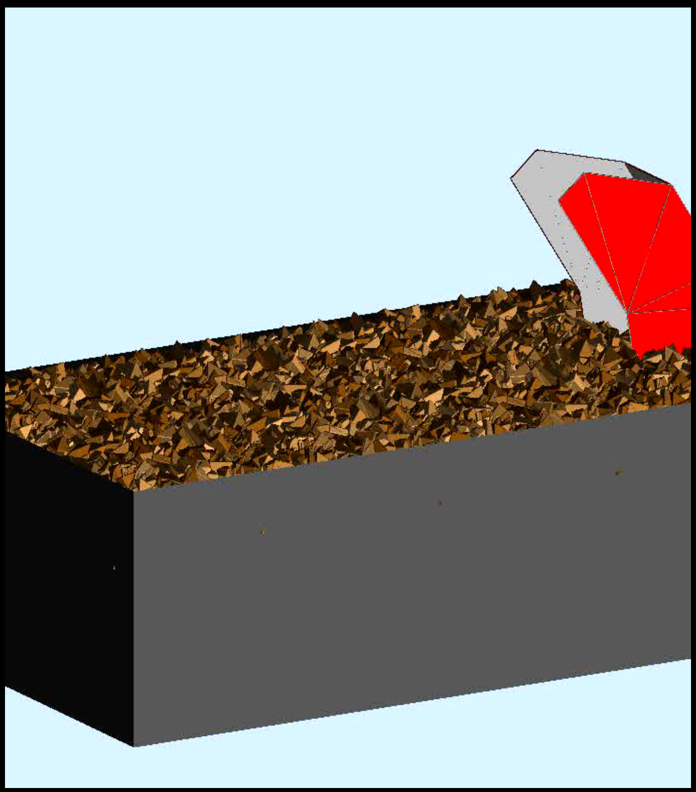
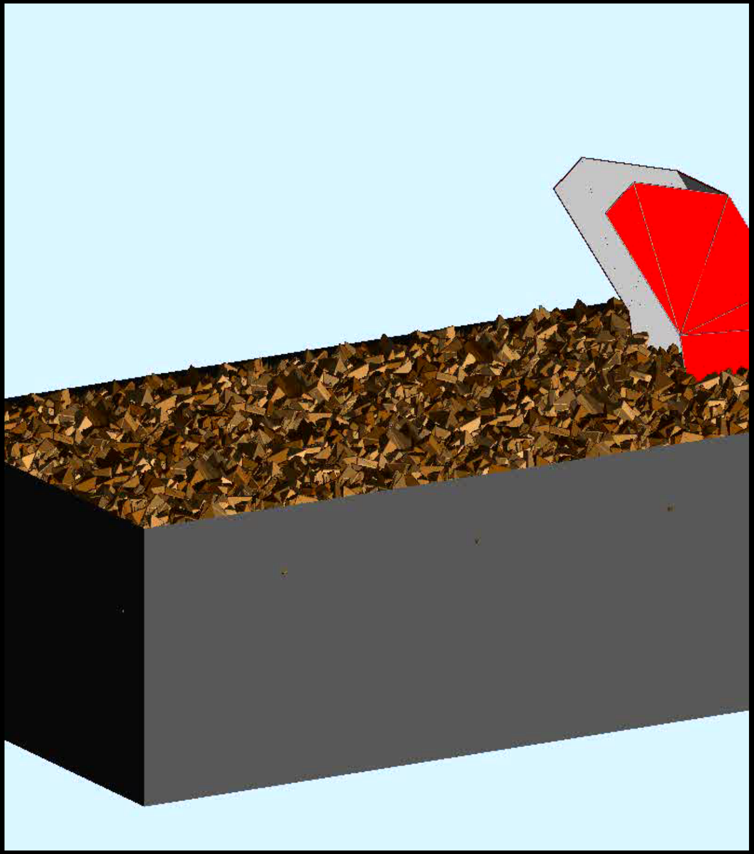
Surveyor Scoop in Loose Soil



Non-percussive
Box: 0.4 x 0.2 x 0.15 m
Speed: 20 mm/s
Depth: 50 mm



Percussive
Box: 0.4 x 0.2 x 0.15 m
Speed: 20 mm/s
Depth: 50 cm
1250 bpm, 2.5 J/blow

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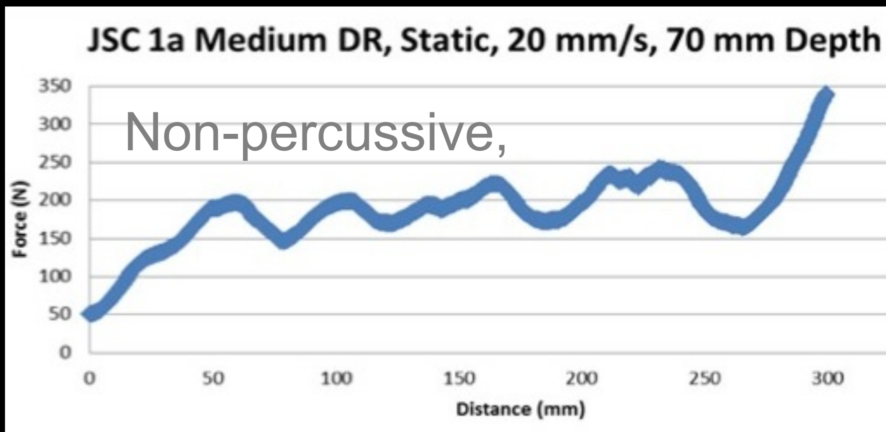
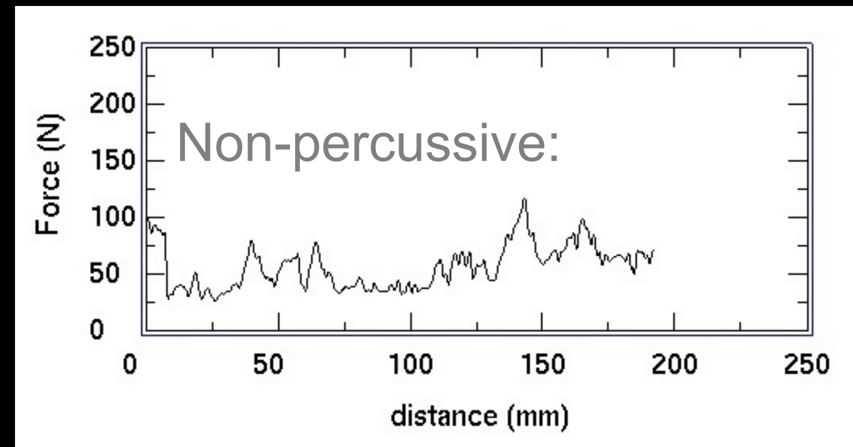
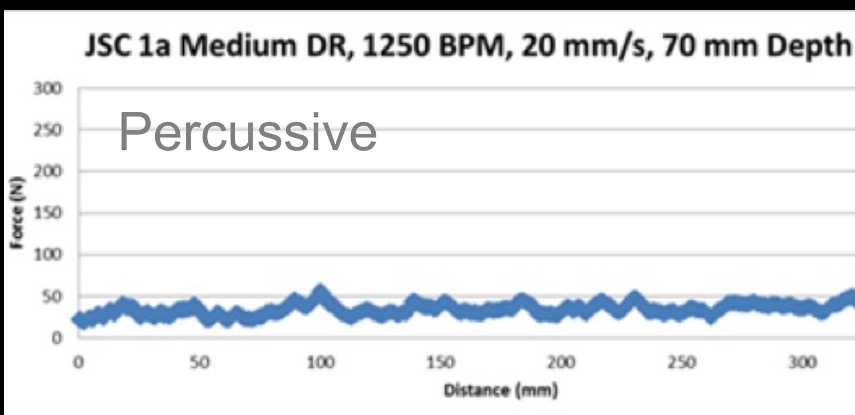
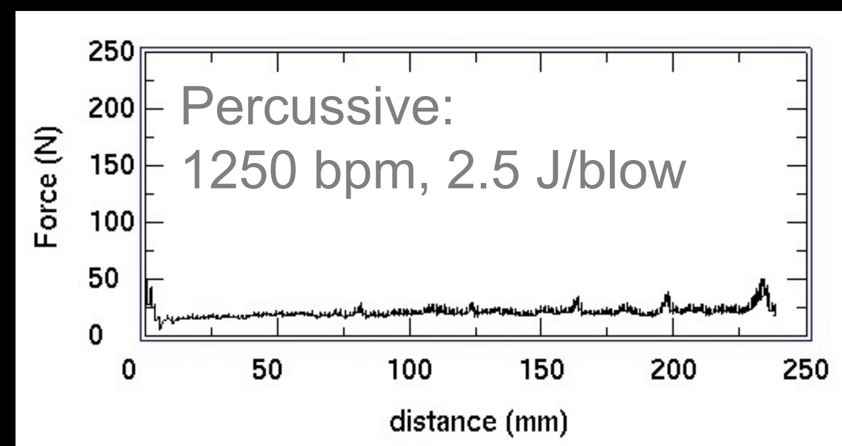
Percussion effect on excavation force









Experimental Results
from Honeybee Robotics
70 mm depth, 20 mm/s

DEM Simulation Results
50 mm depth, 20 mm/s

In Situ Mars Exploration Rover (MER) Scuff Test Simulation

- Scuff test – five MER wheels locked with single wheel rotation
- Objective – use DEM simulation capability to estimate Mars in situ soil properties

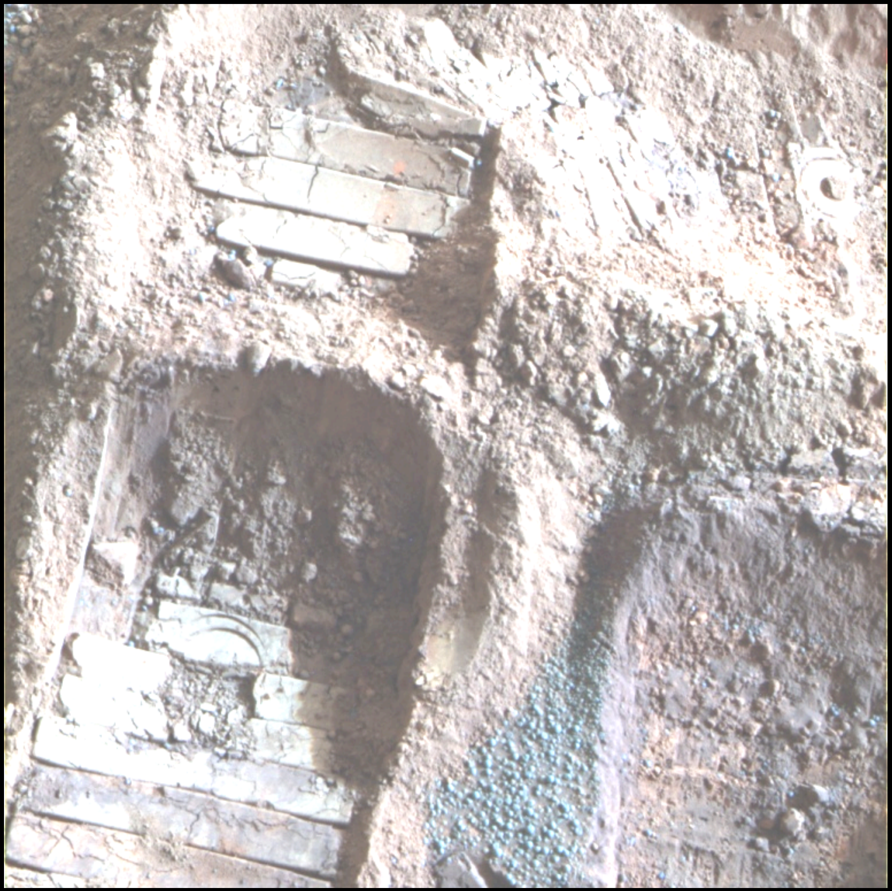


Image of Scuff test during Bsol 371

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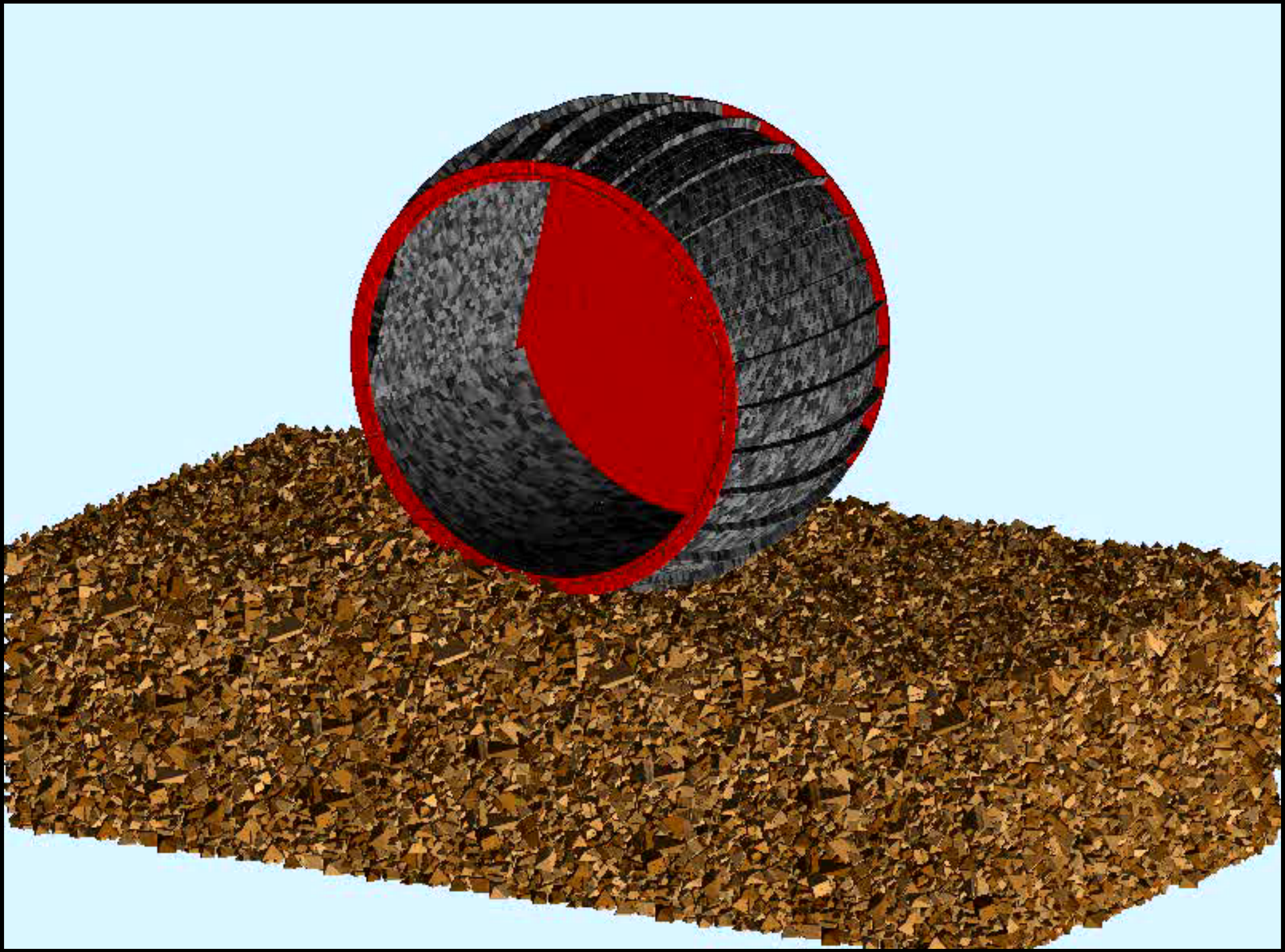
Rover Wheel Simulaiton



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Comparison of DEM and MER in situ scuff tests

Test type	Regolith / DEM particle type	Sinkage (mm)	Wheel Torque (N-m)	Wheel tie-down interaction	Friction angle (deg)
MER in situ Bsol371	Mars regolith	13	16.5	—	
MER in situ Bsol879	Mars regolith	25	11.9	—	
DEM	Poly-ellipse 1	47	5.1	Yes	
DEM	Poly-ellipse 1	38	5.44	No	
DEM	Poly-ellipse 2	44	5.63	Yes	
DEM	Poly-ellipse 2	35	6.03	No	
DEM	Polyhedra	30	6.28	Yes	
DEM	Polyhedra	26	7.03	No	40*

*Sullivan's range of values for Mars regolith friction angles is 30-37°

Neutron Spectroscopy

- New Lunar Science and Exploration Results Enabled by NLSI
- Proposed task:
  - Study the feasibility and operation of hydrogen detection techniques using planetary neutron spectroscopy.
- Required capabilities to complete proposed task:
  - Extend particle transport modeling capability.
  - Develop new neutron analysis techniques.
  - Capabilities available for new work.
- Neutron task results demonstrate unique advantages of NLSI program.

David Lawrence, *JHU/APL*
Rich Miller, *UAH*

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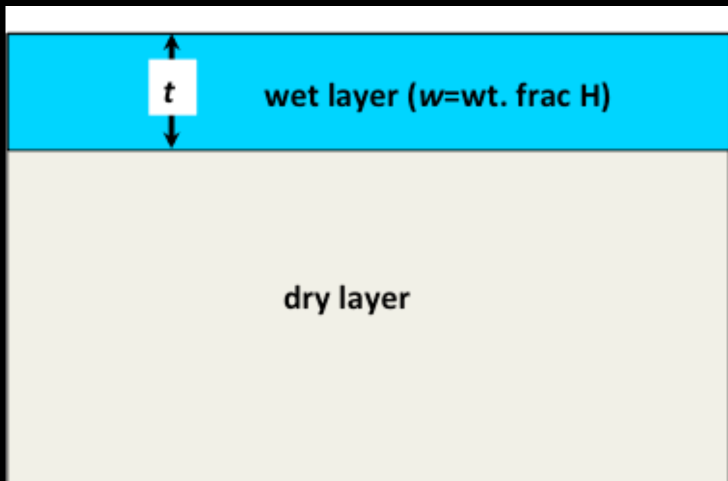
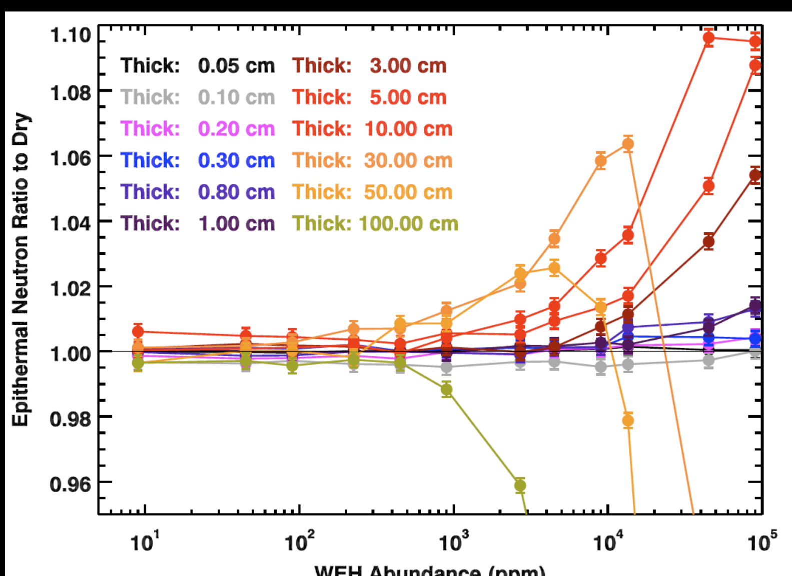
Neutron Detection Limits of Surficial H





Taken from Lawrence et al., (2011)

- NLSI supported study to determine neutron detection limits for surficial H.
  - Existing neutron data may indicate areas of bulk, surficial hydrogen.
- NLSI enabled study by providing rapid response to changing conditions:
  - Study prompted by discovery of surface water by NASA M3 instrument.
- Study was result of NLSI team collaboration between neutron experts and exosphere model experts.
- Results provide value to HEOMD by expanding techniques for resource identification and detection as well as new understanding of lunar volatile processes.

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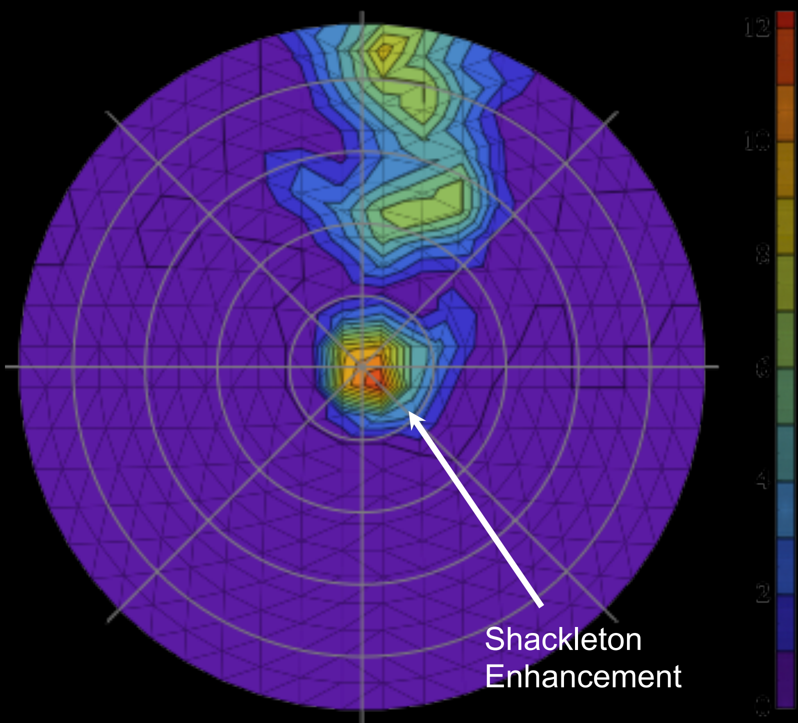
New Polar Hydrogen Detection



South Polar Region Hydrogen Enhancement Likelihood Map

Taken from Miller et al., (2012)

- First detection of fast neutron enhancement at lunar poles.
  - Localized to Shackleton crater.
  - May reveal newly detected hydrogen stratigraphy.
- Study enabled by new analysis techniques funded by NLSI.
- Results locations of near-surface resources for future science and exploration activities.

E/PO Activities

- Formal Education
  - Higher Education: NASA/APL Summer Internship Program
    - Provide hands-on research opportunities to undergraduate and graduate students, mentored by the NLSI team at APL
  - High School Educators Workshop: “Unknown Moon” Institute
    - June 24-28, 2013 at APL (fourth year for workshop)
  - Space Academy for middle-school students on May 3

- Informal Education
  - InOMN in partnership with the Maryland Science Center in 2011, 2012, and planned for 2013

- Outreach
  - NLSI Website: www.lunarpoles.jhuapl.edu

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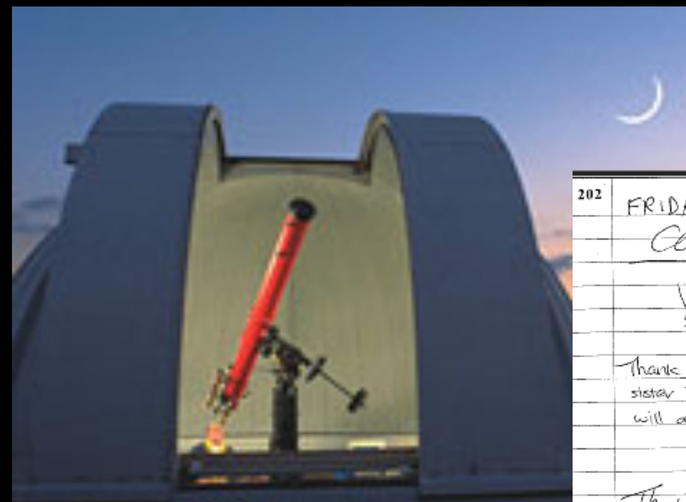
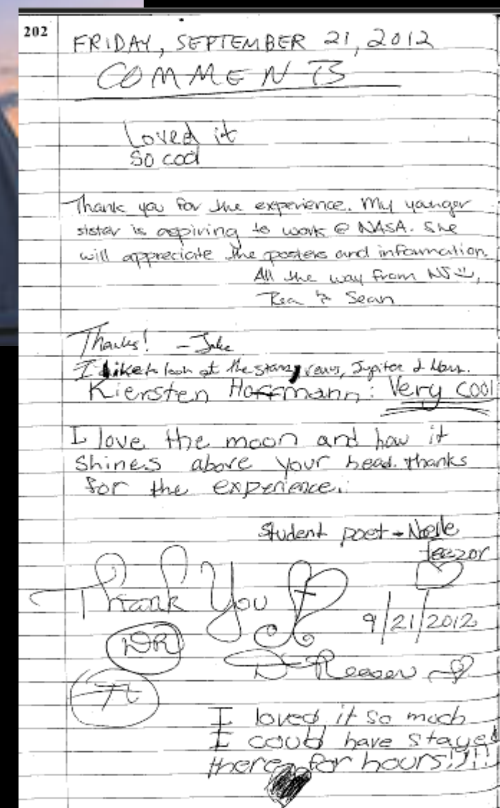
Formal Education Highlights

- **Workforce development (internships)**
- **Unknown Moon Institute in 2012 (at LPI)**
  - In partnership with LPI, included 20 high school and middle school STEM teachers
  - Activities focused on basic Moon-Earth concepts and NLSI research
  - Next workshop at APL June 24-28, 2013
  - Evaluation results show consistently positive remarks from participants
- **Space Academy**
  - Students are given standards-based activities to complete in the classroom before visit
  - Day included a question and answer session with NLSI APL scientists and engineers; demonstrations from APL's Space Simulation Lab

Informal Education Highlights

- **International Observe the Moon Night (InOMN)**
  - Partner with the Maryland Science Center for their Stargazer Fridays event, which makes their roof-top observatory open to the public
  - NLSI scientists from APL support the night, interacting with MSC visitors and the night includes multiple hands-on lunar science activities





202 FRIDAY, SEPTEMBER 21, 2012
COMMENTS

Loved it
So cool

Thank you for the experience. My younger sister is aspiring to work @ NASA. She will appreciate the posters and information. All the way from NJ,
Rea & Sean

Thanks! –Jake
I liked look at the stars, Jupiter & Mars.
Kiersten Hoffmann: Very cool

I love the moon and how it shines above your head. thanks for the experience.

Student poet – Noelle Lezzor

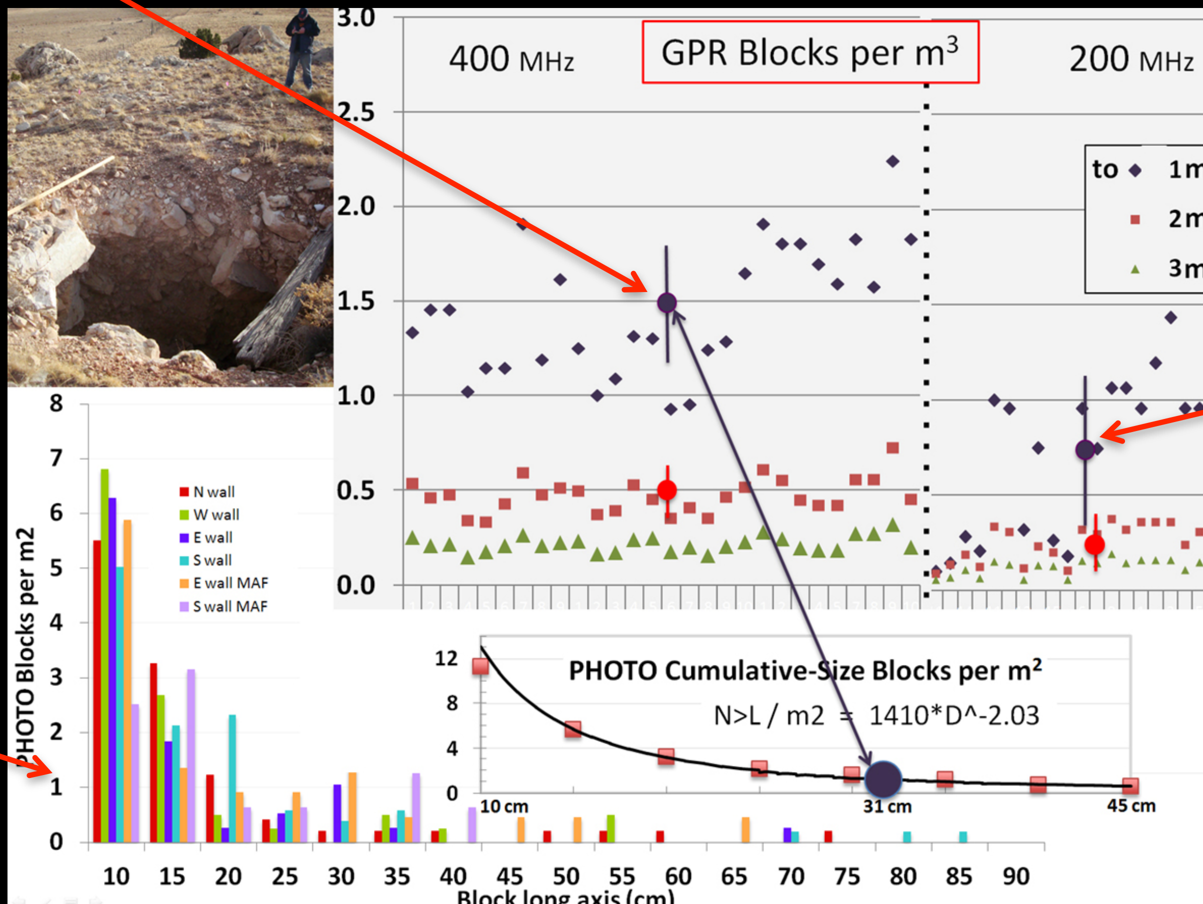
Thank You
9/21/2012

I loved it so much I could have stayed there for hours!!!

Predicting Block Distribution Using GPR

Block distribution using shorter wavelength:
Does a good job in near surface, but under estimates at depths over1-2 m due to scattering (predictable)

John Grant, *SI*
Patrick Russell, *SI*



Block distribution Using longer wavelength: Underestimates even in near surface, but does so in a predicable fashion

Block distribution measured in field at Meteor Crater

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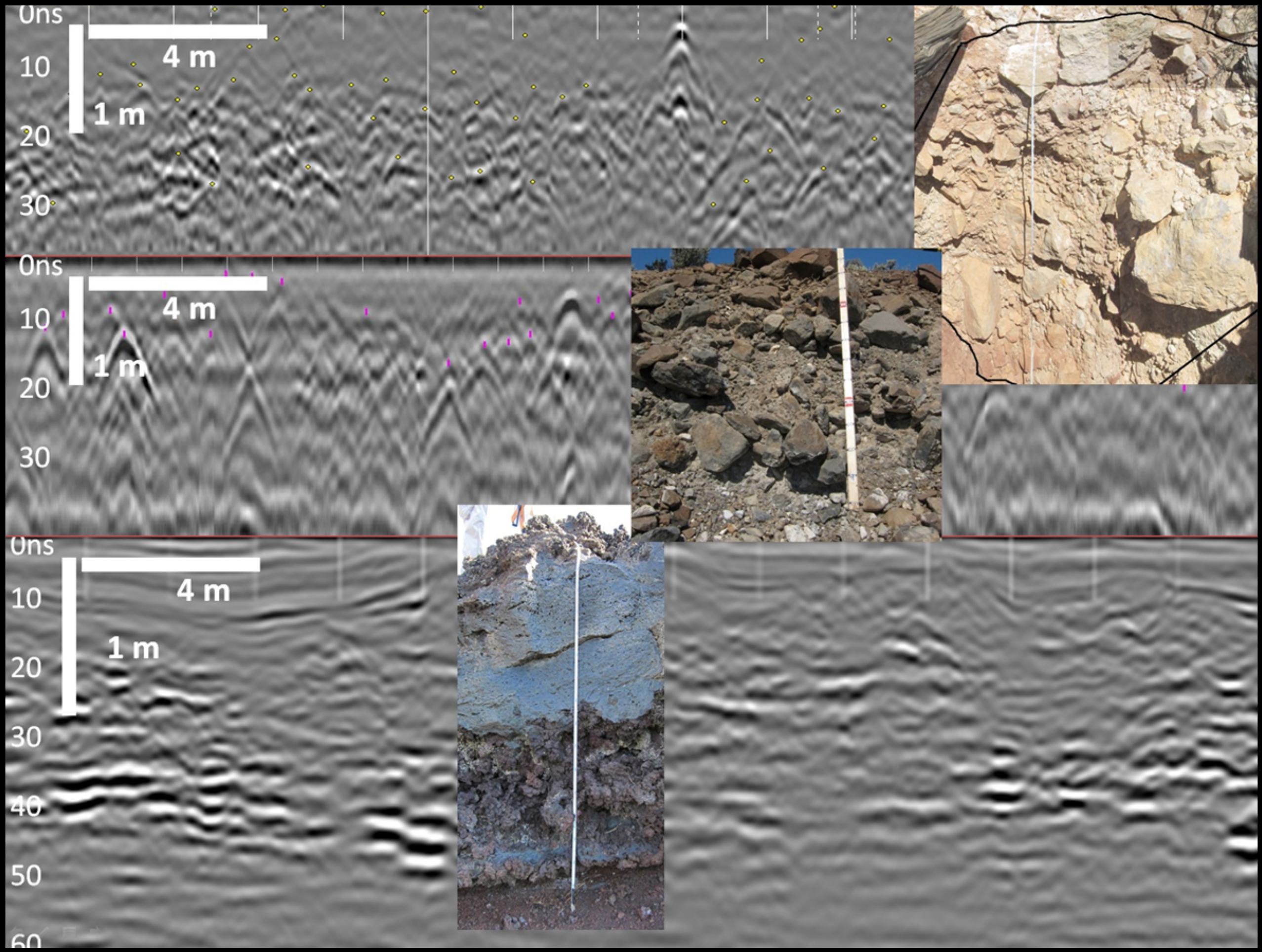
Comparing GPR Signatures from Different Environments

Efforts like those shown on Previous Page Can Quantify Visually Different Signatures for Multiple Environments, Thereby Allowing them to be Distinguished Using GPR

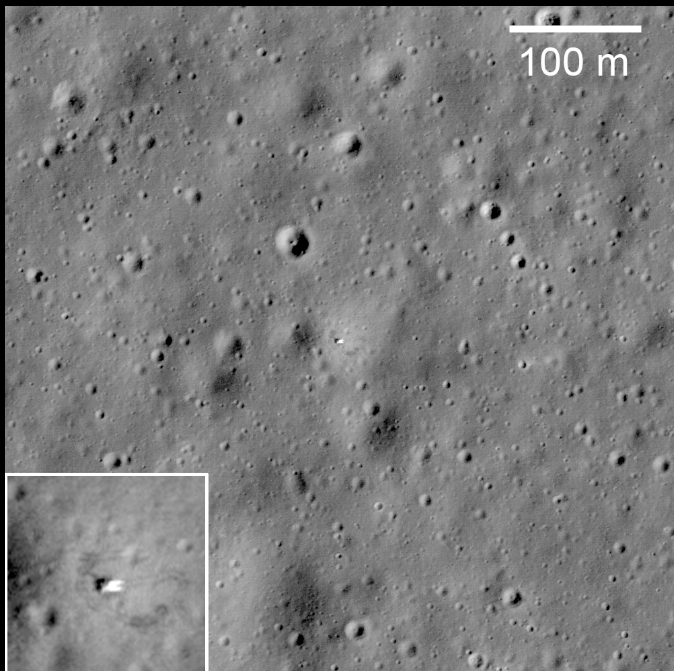


Meteor Crater, Ejecta

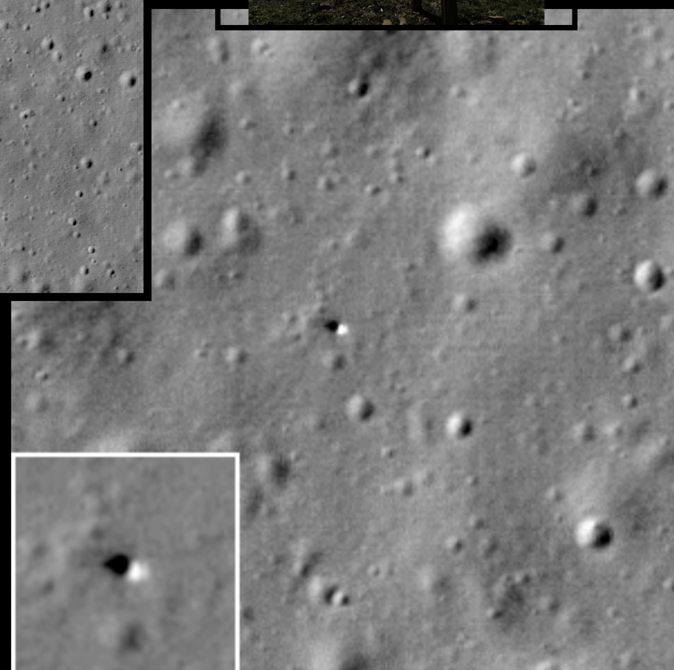
Sunset Crater, Aa flow

Columbia Plat., Flood Basalt

Luna 17 - Lunokhod 1



Luna 17



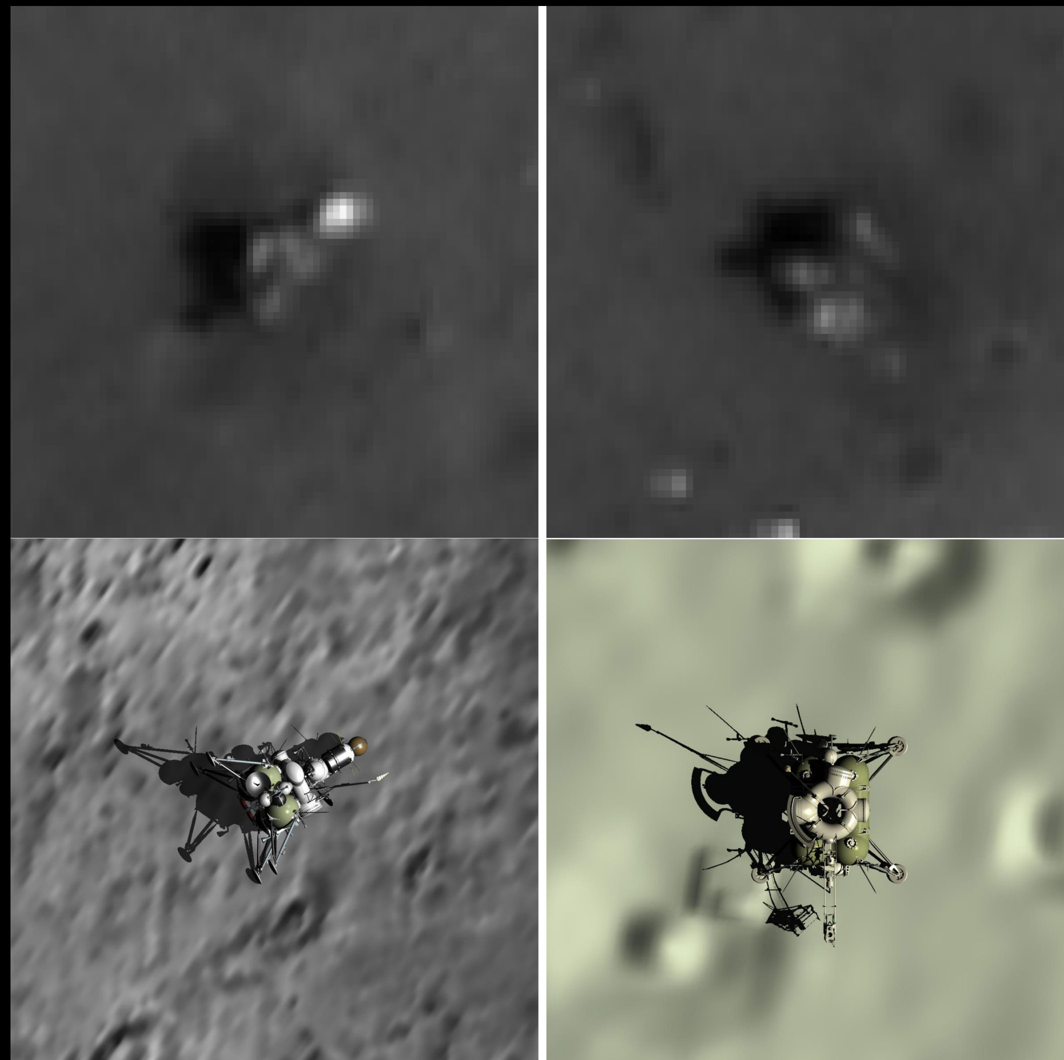
Lunokhod 1

- Earth-based laser ranging for a few days during the mission, subsequently no signal.
- LROC images used to locate the rover.
- Coordinates sent to T. Murphy UCSD, subsequently he used Apache Point Lunar Laser to locate the rover.
- Signal strength excellent.
- Significantly expands the spatial extent of the network of reflectors – better lunar geodesy and relativistic physics

Northwest Mare Imbrium
Landed: November 17, 1970
EOM: September 14, 1971
Lander and Rover: 1814 kg

Jeff Plescia, *JHU/APL*

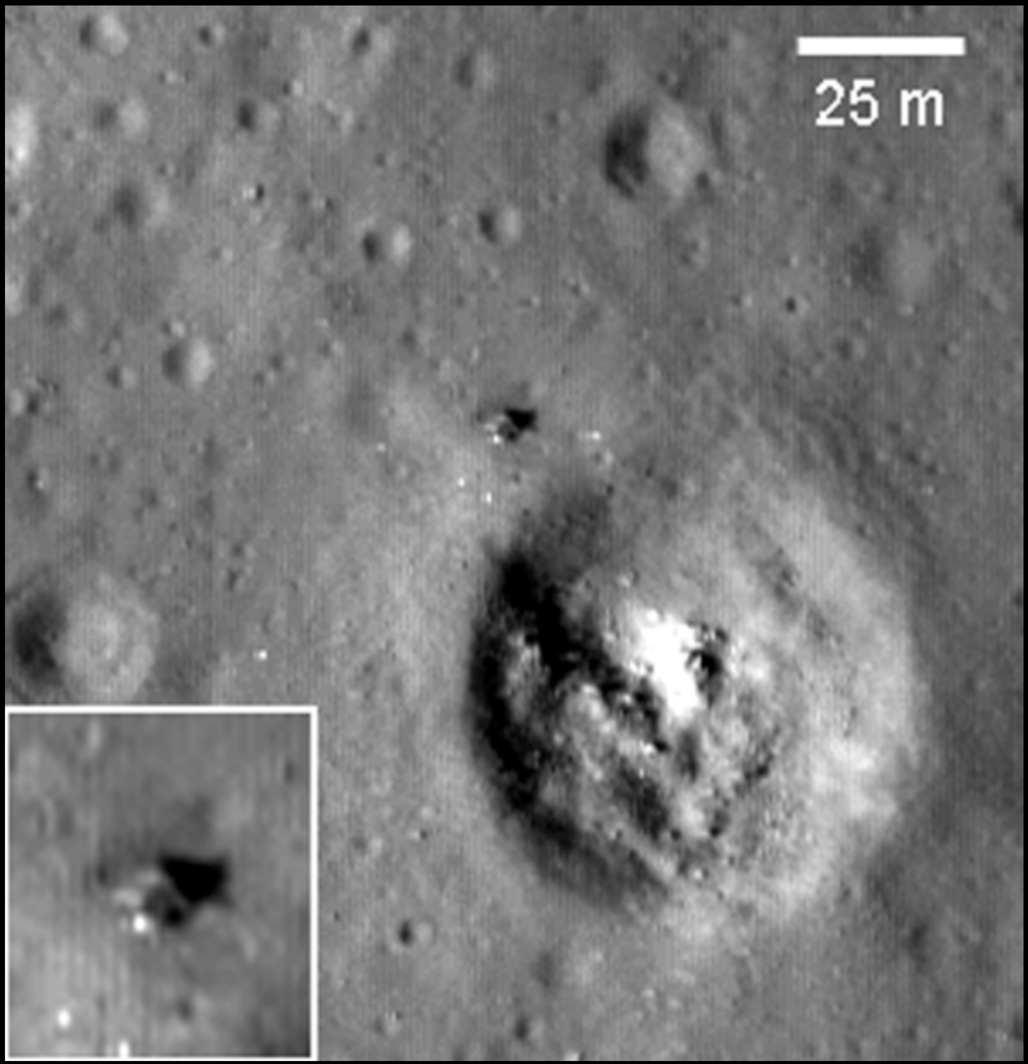
Luna 23 and 24



Luna 23 - Failed - Overturned Entire Vehicle on Side

Luna 24 - Successful - Only Lower Stage Remains on Surface

Luna 24



Landing site: Mare Crisium
Mission conducted at night.
No surface imaging
Northwest flank of a 63 m crater.

Fresh crater: crisp morphology and bright rays to the NW - W – SE, absent to the NE. Sample site is on continuous ejecta.

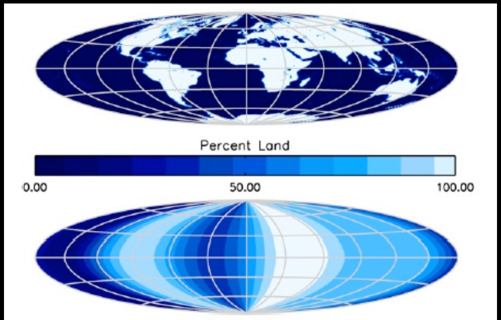
Crater maybe secondary to Giordano Bruno. Luna 24 samples being studied: Plescia and Norman (ANU) to determine age of Bruno from melt material.

The Moon as a Platform: Observing the Earth as a Distant Planet

CLOVE (Camera for Lunar Observations of the Variable Earth)

A lunar pole based instrument concept to remotely characterize the physical and biological signatures of Earth over long timescales to inform future studies of Earth-like exoplanets.

Autonomous or astronaut deployable "suitcase" experiment.

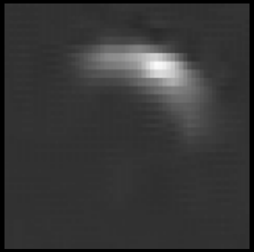


Even with no spatial resolution, a photometric time series allows us to recover the land distribution of the planet (Cowan et al 2009). Future large space telescopes will exploit this approach.

Photometry/Spectroscopy

Earth represents ground truth – *we have simultaneous spatially resolved AND unresolved photometry and spectroscopy, allowing us to test how well we can reconstruct 2D information from spatially-unresolved time series data.*

The Moon represents an excellent platform for long term monitoring to reveal trends on all timescales. With observations of Earth from the Moon we can optimize our chances of success in exoplanets and enhance our ability to characterize planets, and ultimately detect life



Glint from Earth in LCROSS data: oceans or ice clouds?

Polarimetry in Extrasolar Planet Observations

Detection – terrestrial planets are polarized, stars are not; aids detection and mission design
Characterization – "2nd spectrum" clouds, oceans, Rayleigh scattering, solid surfaces
ExtraZodiacal disks – geometry revealed, inclination, line of nodes; dust properties.
Detection of Life – circular polarization as remote sensing tool for chirality hence biology

Bill Sparks, Mark Postman, Carol Christian, Peter McCullough, *STScI*
Vicky Meadows, Tyler Robinson, *U. Wash.* Kimberly Ennico, *NASA Ames*

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Observing the Earth as a Distant Planet

SPACE TELESCOPE SCIENCE INSTITUTE

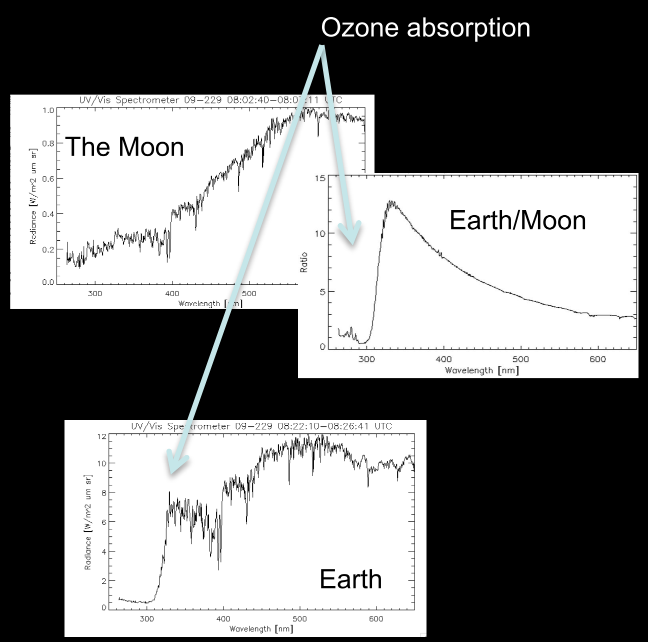
Strategy

- Strong collaboration with LCROSS team fostered through NLSI
  - Interpret LCROSS spectroscopic and imaging data of Earth
- Leveraging work within NASA Astrobiology institute (co-I Meadows)
  - Develop sophisticated Earth models for times of LCROSS observations
  - Validate models with data
- Excellent synergy between NLSI, NAI and LCROSS

Results:

- *Highlight: ozone from LCROSS – huge signal at NUV; due to life on Earth*

- LCROSS aperture smaller than Earth disk
  - Enhance models to handle this
  - Enables a variety of scenes to be observed including ice caps, oceans, continents
- ***With empirical Earth spectroscopy we will improve our ability to characterize extrasolar planets and model them.***



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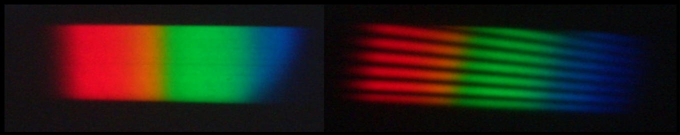
The Moon as a Platform: Polarization Observations from Space & a New Approach to Polarimetry

SPACE TELESCOPE SCIENCE INSTITUTE

Issue

- Polarimetry is potentially critical in extrasolar planet observations
  - ***Detection*** – terrestrial planets are polarized, aids detection and mission design
  - ***Characterization*** – clouds, oceans, Rayleigh scattering, solid surfaces
  - ***ExtraZodiacal disks*** – geometry, inclination, dust properties
  - ***Detection of Life*** – circular polarization as remote sensing tool for chirality
- Polarimetry typically requires fragile, complicated, modulating components. Difficult or low accuracy from space.
- *We wanted to include polarimetry in CLOVE*



Unpolarized Polarized

Solution:

- ***We invented a new method for spectropolarimetry ideal for space:***
  - robust static optics, no moving parts, single data frame, light weight, compact, full Stokes (Sparks et al 2012 Applied Optics).
- Encode Stokes parameters as coefficients of orthogonal polynomials perpendicular to wavelength direction. All data on a single frame. Next step – build an instrument!

Observing the Earth as a Distant Planet: Earthshine polarimetry and Fieldwork

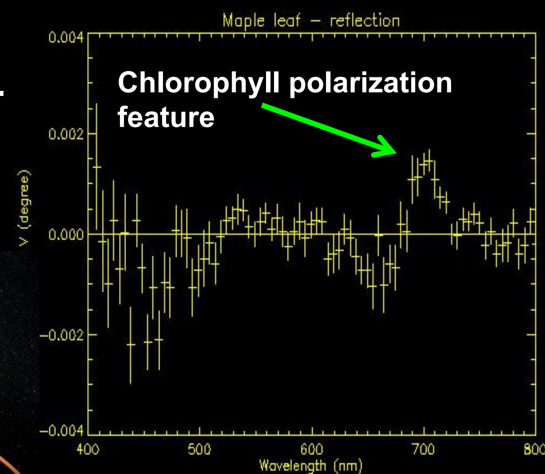
Strategy

- Building on earlier lab work, we made field measurements of circular polarization to attempt direct detection of biosignatures based on life's chirality.

- Field observations show circular polarization.

Smithsonian Environmental Research Center

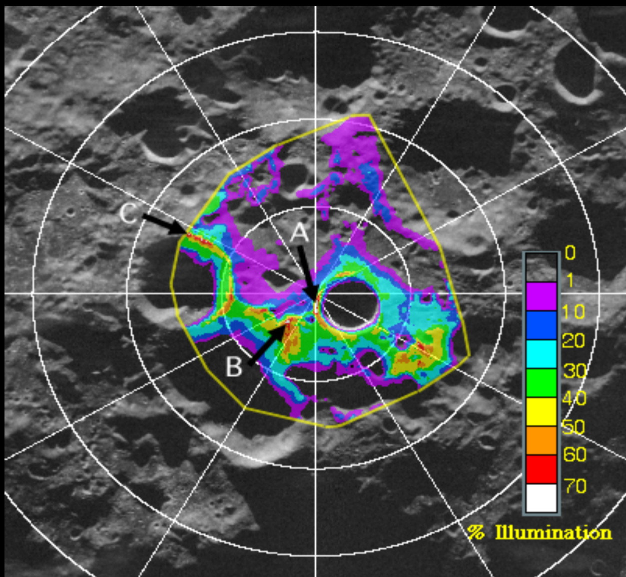
In the very long term, needing large space-based telescopes, a method like this might provide unequivocal evidence of life on other worlds



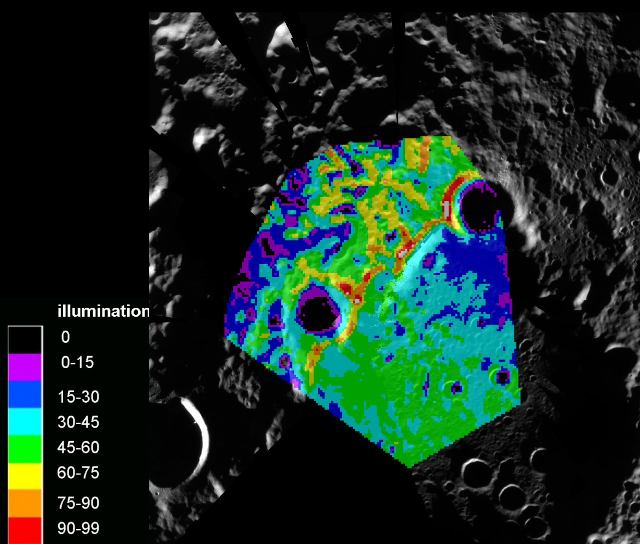
- Measure polarization of Earthshine to estimate integrated polarization of Earth
    - We have helped nurture a student experiment at the University of Louisville to monitor the polarization of the Earthshine.

NLSI Lunar Polar Science & Exploration

Quantitative Illumination Maps

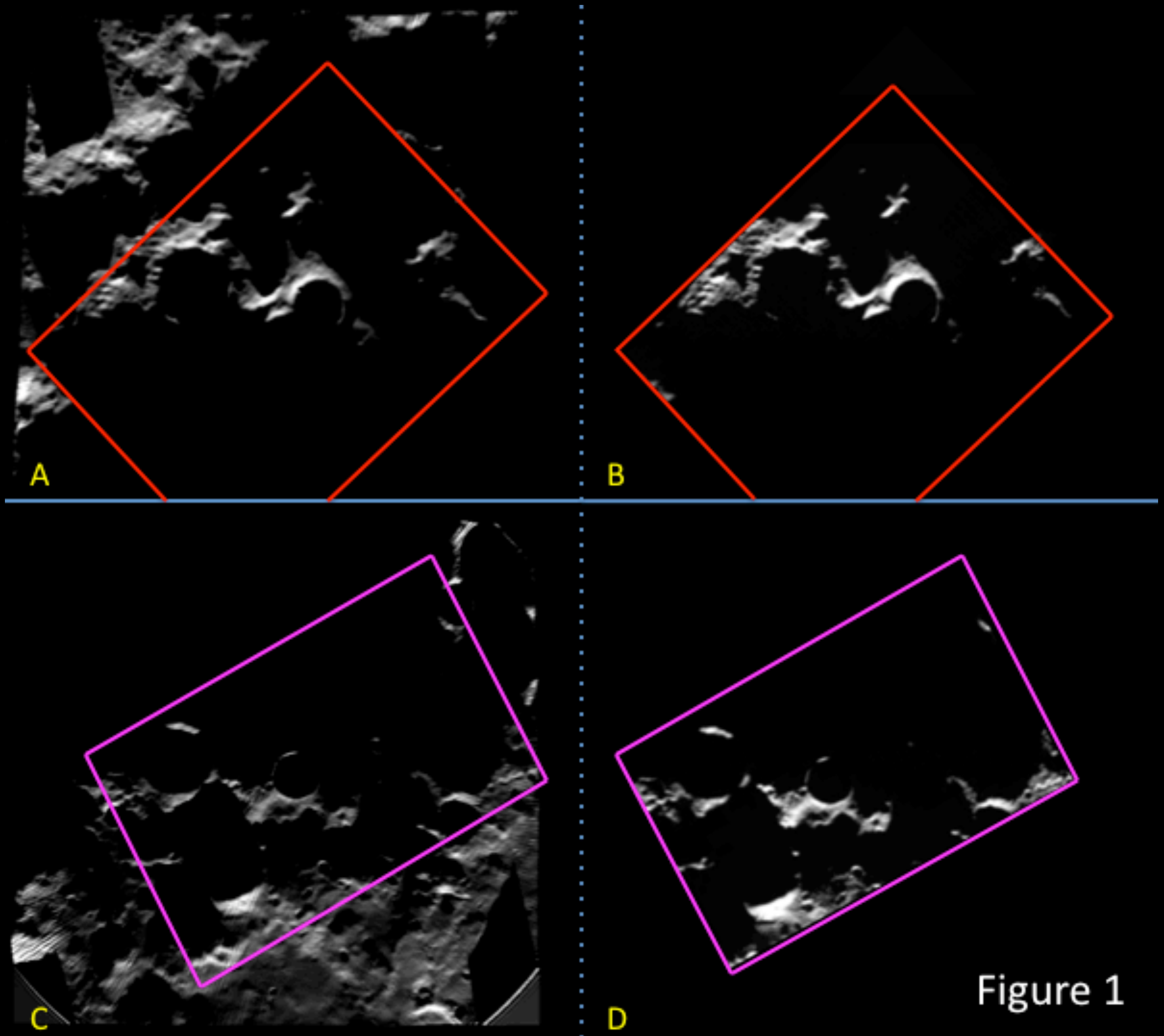


- No constant illumination
- A,B,C lit more than 70% of a winter day
- A&B collectively lit > 98%



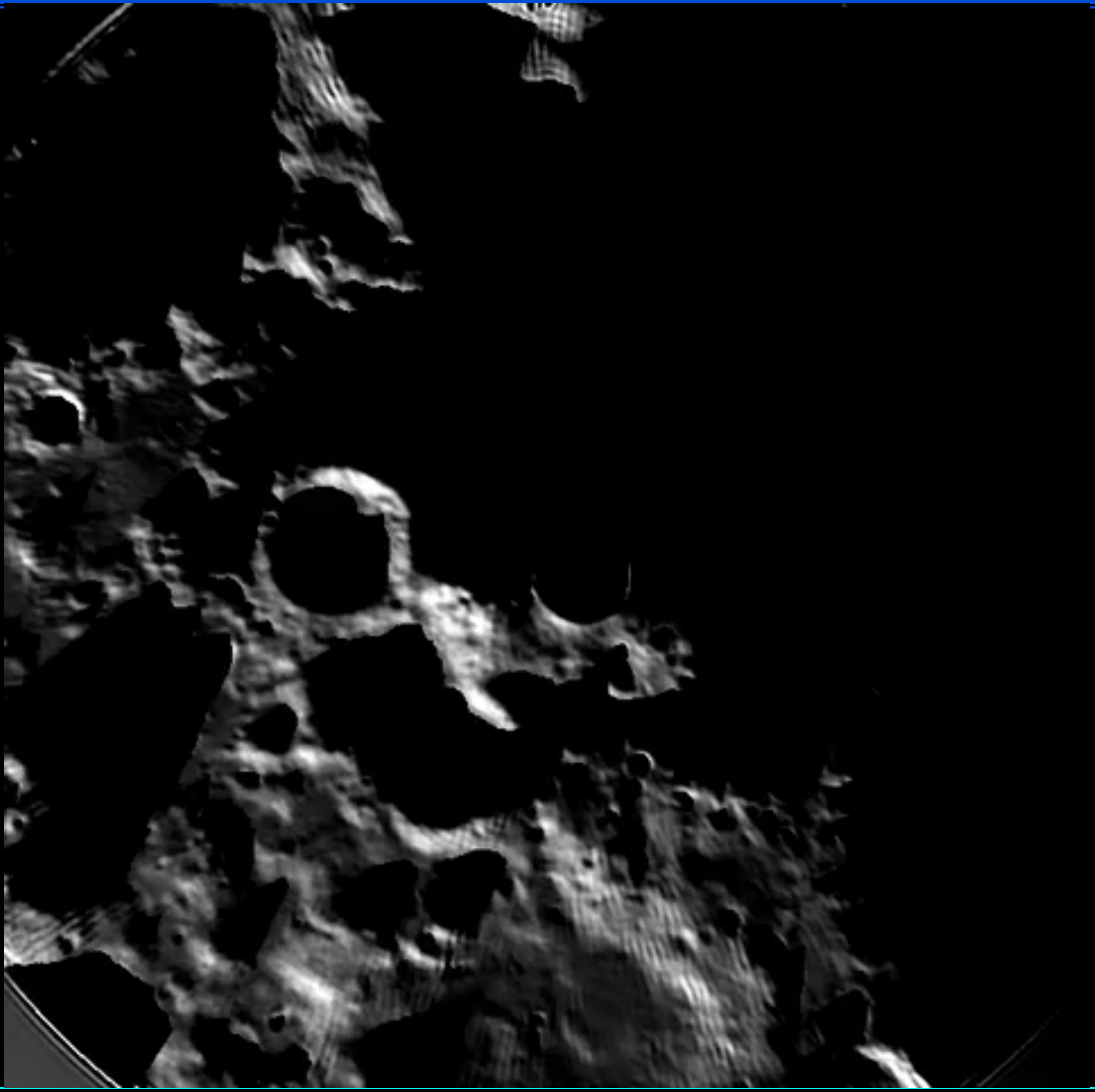
- Four places on the rim of Peary crater were constantly illuminated during a lunar summer day
- All are in close proximity with permanently shadowed regions.

Kaguya-Clementine Comparison



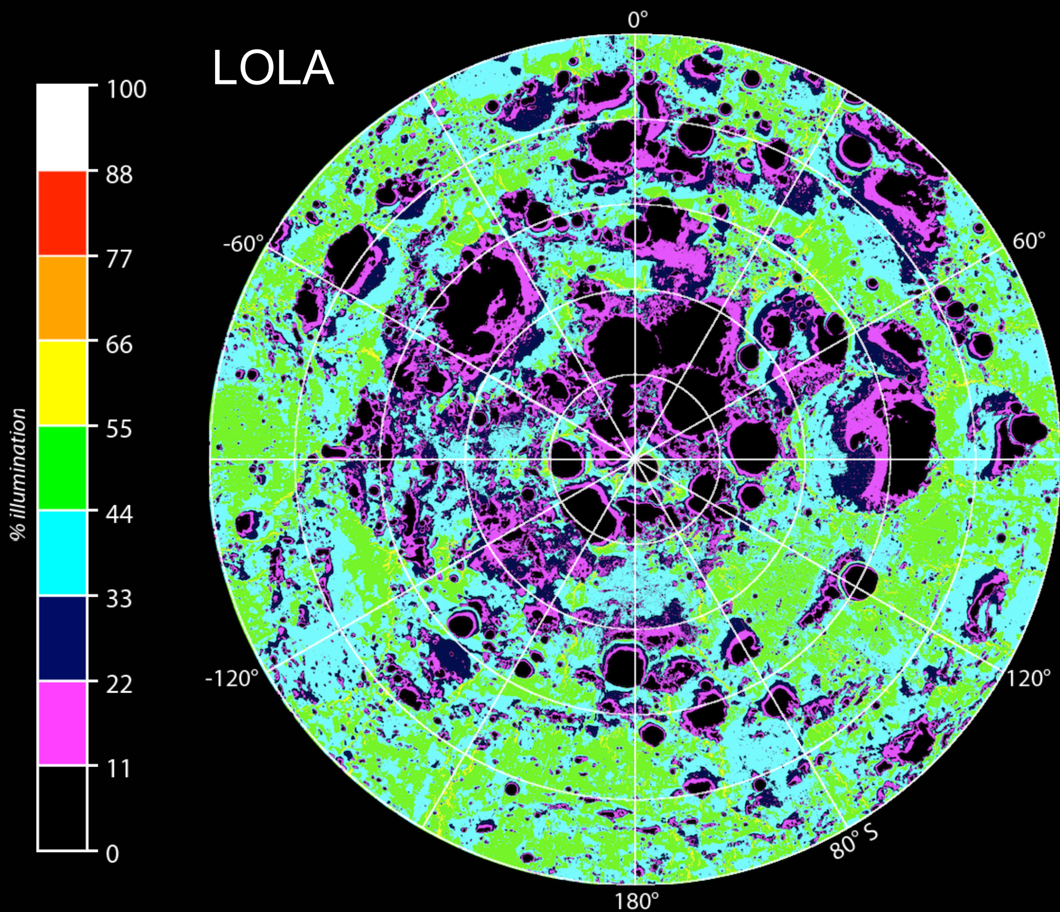
From Bussey et al., (2010) Illumination Conditions of the South Pole of the Moon Derived using Kaguya Topography, Icarus

Kaguya Simulation Movie

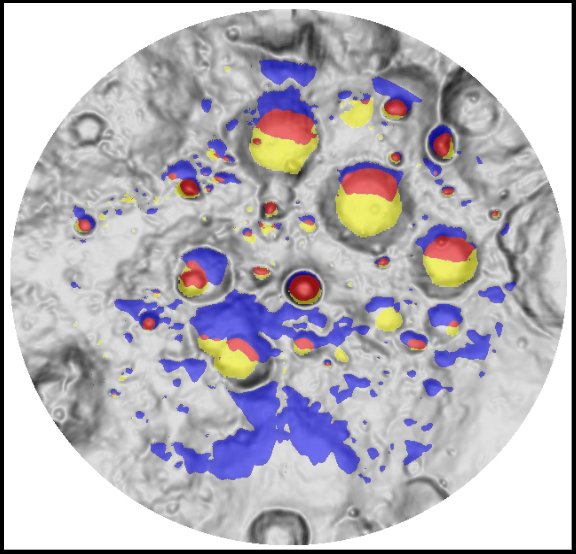


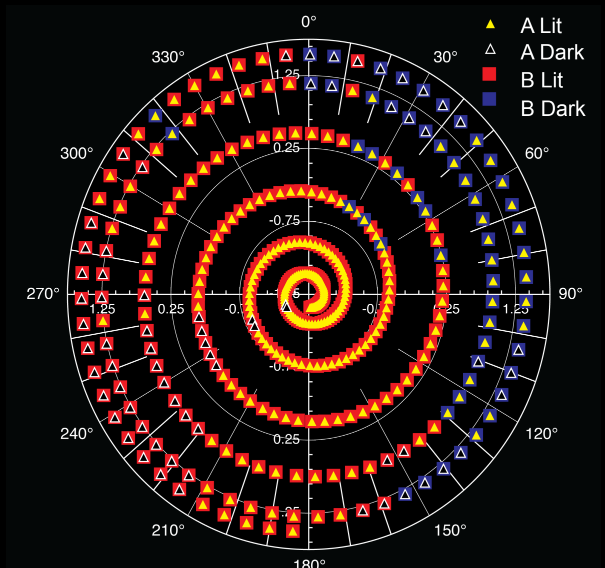
N L S I
Lunar Polar
Science & Exploration

South Pole Illumination

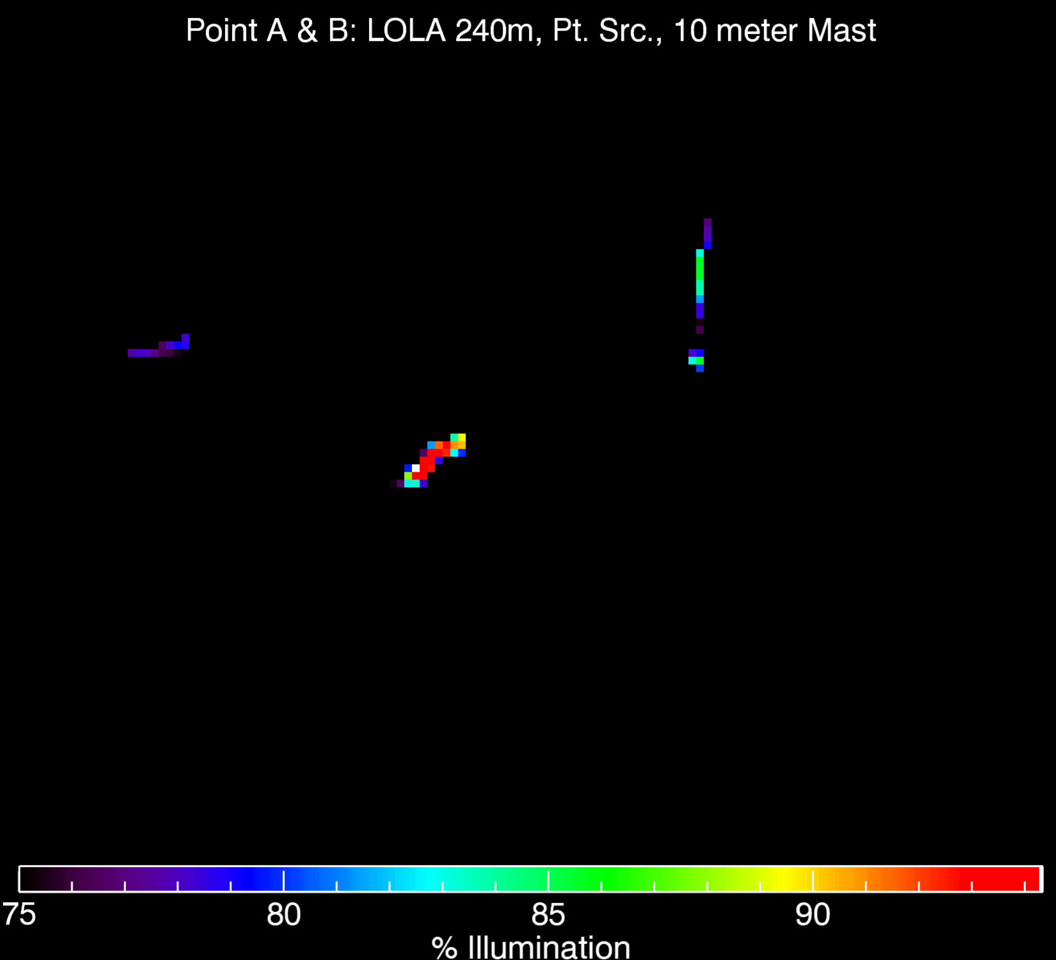


Mean South Pole Illumination
One Year: Days 1-355 (LOLA)





Increasing Illumination with Increasing Mast



Comms too!

Polar Illumination Results

- Post the recent armada of international missions, we now have topography and image data with sufficient fidelity to fully characterize the polar illumination conditions
  - Maximum single period of illumination
  - Determine all eclipse periods
  - Exact shadow locations
  - Effect of mast height
- Also discovered that permanent shadow can exist as far from the poles as 58°
  - Implications for easier access to volatiles
- Capability helped facilitate numerous unplanned collaborations

Lunar Exploration Roadmap (LER)

Why should we go back to the Moon?

Science (Sci) Theme: Pursue scientific activities to address fundamental questions about the solar system, the universe, and our place in them

Feed Forward (FF) Theme: Use the Moon to Prepare for Future Missions to Mars and Other Destinations

Sustainability (Sust) Theme: Extend Sustained Human Presence to the Moon to Enable Eventual Settlement

- Feed Forward: Moon to enable exploration of other destinations.
- Science: understanding terrestrial planets.
- Sustainability is the key:
  - ISRU Development early;
  - Commercial “on ramps” (jobs);
  - International cooperation.

http://www.lpi.usra.edu/leag/ler_draft.shtml

THEMES → GOALS → OBJECTIVES → INVESTIGATIONS

Lunar Exploration Roadmap (LER)

How the Polar Team addresses LER Investigations

- **Investigation-Sci-A-3A**: Map and characterize polar cold traps.
- **Investigation-Sci-A-3B**: Map and characterize quasi-permanently illuminated areas.
- **Investigation-Sci-A-4A**: Characterize the structure and layering of the regolith.
- **Investigation-Sci-A-7B**: Determine how impacts modify, redistribute, and mix materials.
- **Investigation-Sci-B-2A**: Characterize volatile concentrations and their variability.
- **Investigation FF-C-1A**: Determine the distribution of volatile components.

http://www.lpi.usra.edu/leag/ler_draft.shtml

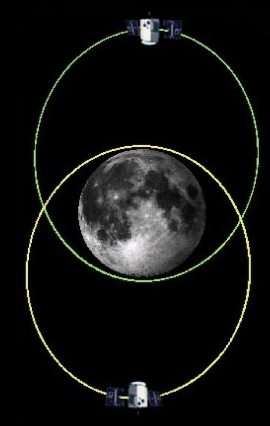
An Affordable Lunar Return Architecture

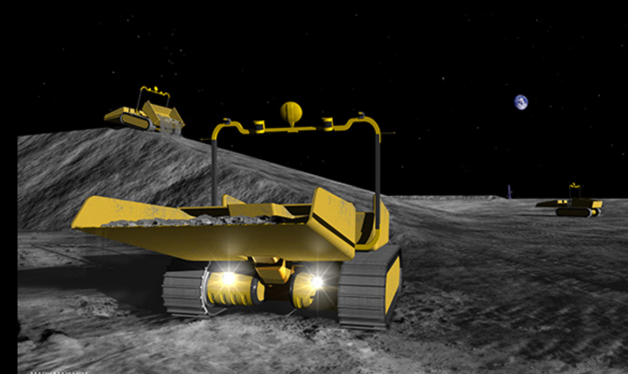
- **Mission**
  - Create a permanent human-tended lunar outpost to harvest water and make propellant
- **Approach**
  - Small, incremental, cumulative steps
  - Robotic assets first to document resources, demonstrate production methods
  - Teleoperation of robotic mining equipment from Earth. Emplace and build outpost assets remotely
  - Use existing LV, HLV if it becomes available
- **Cost and Schedule**
  - Fits under existing run-out budget (< $7B/ year, 16 years, aggregate cost $88 B, real-year dollars)
  - Resource processing outpost operational halfway through program (after 18 missions); end stage after 30 missions: 150 mT water/ year production
- **Benefits**
  - Permanent space transportation system
  - Routine access to all cislunar space by people and machines
  - Experience living and working on another world

P.D. Spudis and A.R. Lavoie (2011) Using the Resources of the Moon to Create a Permanent Cislunar Space Faring System. Space 2011 Conf, Long Beach CA, AIAA 2011-7185, 24 pp.

Initial Steps

- **1. Communication/navigation satellites**
  - Polar areas out of constant Earth LOS; need comm, positional knowledge
- **2. Polar prospecting rovers**
  - Study and characterize water deposits, other substances, environment
- **3. ISRU demo**
  - Heat icy regolith to extract water; purify and store as ice in cold traps
- **4. Digger/Hauler rovers**
  - Excavate regolith, transport feedstock to fixed stations for water extraction
- **5. Water tankers**
  - Purify and store extracted water





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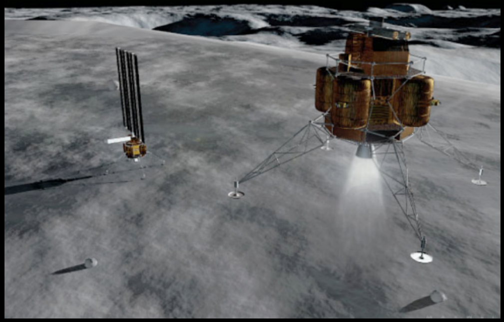
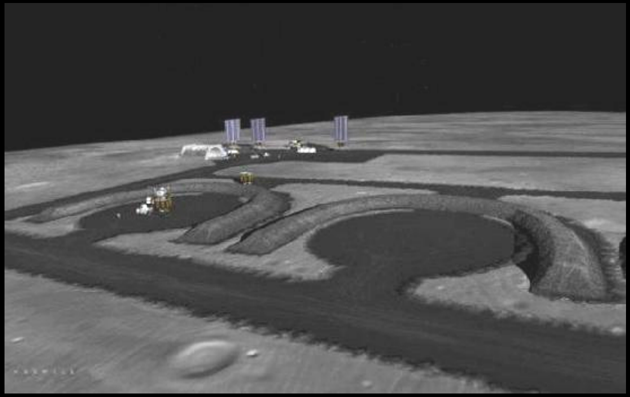
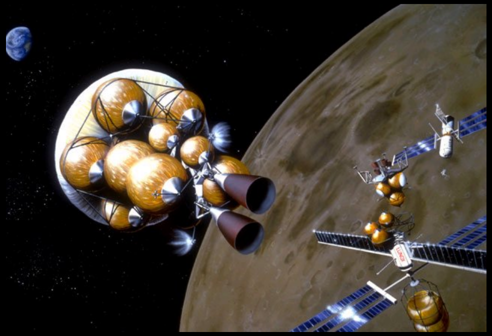
Next Steps

- **6. Electrolysis units**
  - Crack water into hydrogen and oxygen; liquefy into cryogens
- **7. Supporting equipment**
  - Robotic Landers - medium (500 kg payload), heavy (2 mT payload)
  - Power plants - extendable solar arrays, steerable on vertical axis to track sun at poles
  - Cryo storage - store LOX, LH_2 (use cold traps, 25 K)
  - Material Fabricators - Process regolith for rapid prototype products and parts
- **8. Space-based assets**
  - LEO depot - fuel lunar departure stages
  - LLO depot - staging node for reusable cargo and human landers







NLSI Advantages
Take Home Message

Longer periods of performance and broader funding levels resulted in:

- Unexpected benefits from multiple teams' collaborations
- Rapid response to changing research environments
- Creating inter-team and interdisciplinary collaborations
- Long term stability for student and future workforce development
- Creates pathways for large scale international collaborations that aren't normally available through typical R&A grant programs

Example of Cross-Team Studies

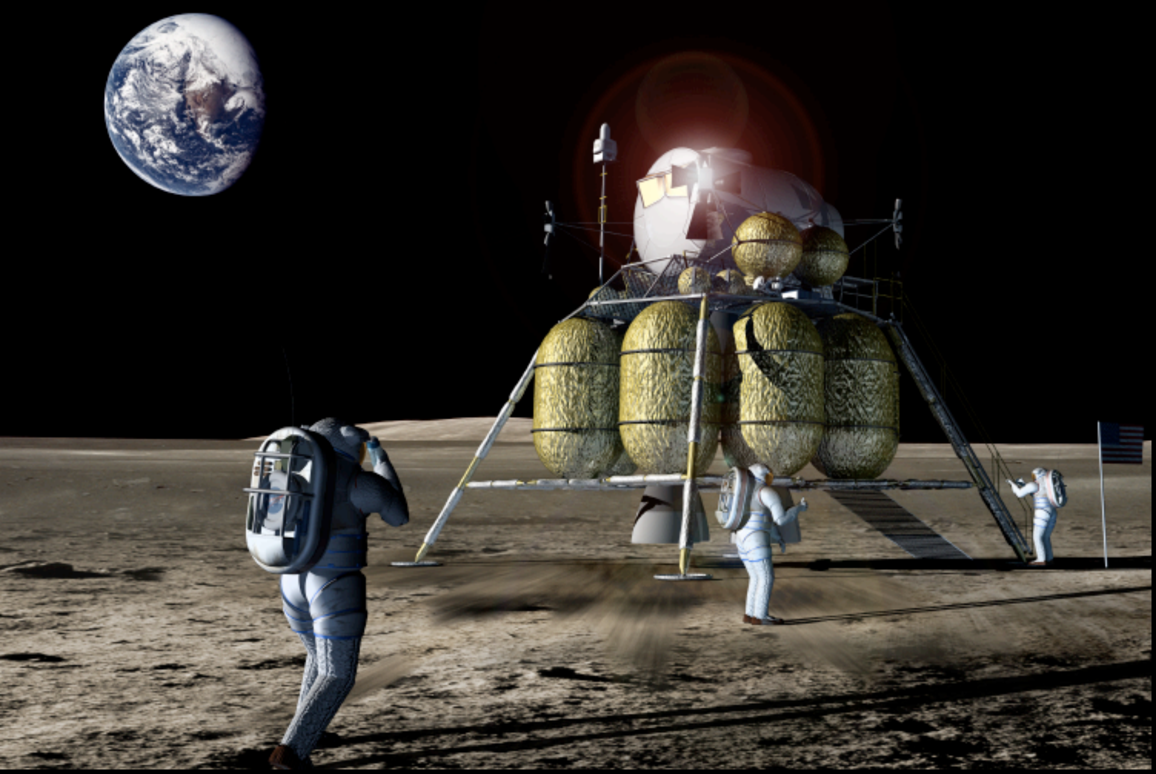
- Participants
  - Bill Farrell's DREAM team (Farrell, Killen, Hodges, Elphic, Keller)
  - Ben Bussey's Polar team (Hibbitts, Orlando, Poston, Grieves, Dyar, Klima, Hurley)

- Exchange
  - DREAM identifies surface chemistry parameters regarding adsorption of volatiles on lunar regolith that are not well known
  - Polar runs lab experiments to determine values

- Benefits
  - Guidance of Polar team toward most important problems
  - Better values of physical parameters for DREAM to include in numerical models

- Results
  - Increased understanding of the distribution of H_2O/OH on the surface of the Moon

The Lunar Poles:
An Ideal Site for Scientific Exploration?



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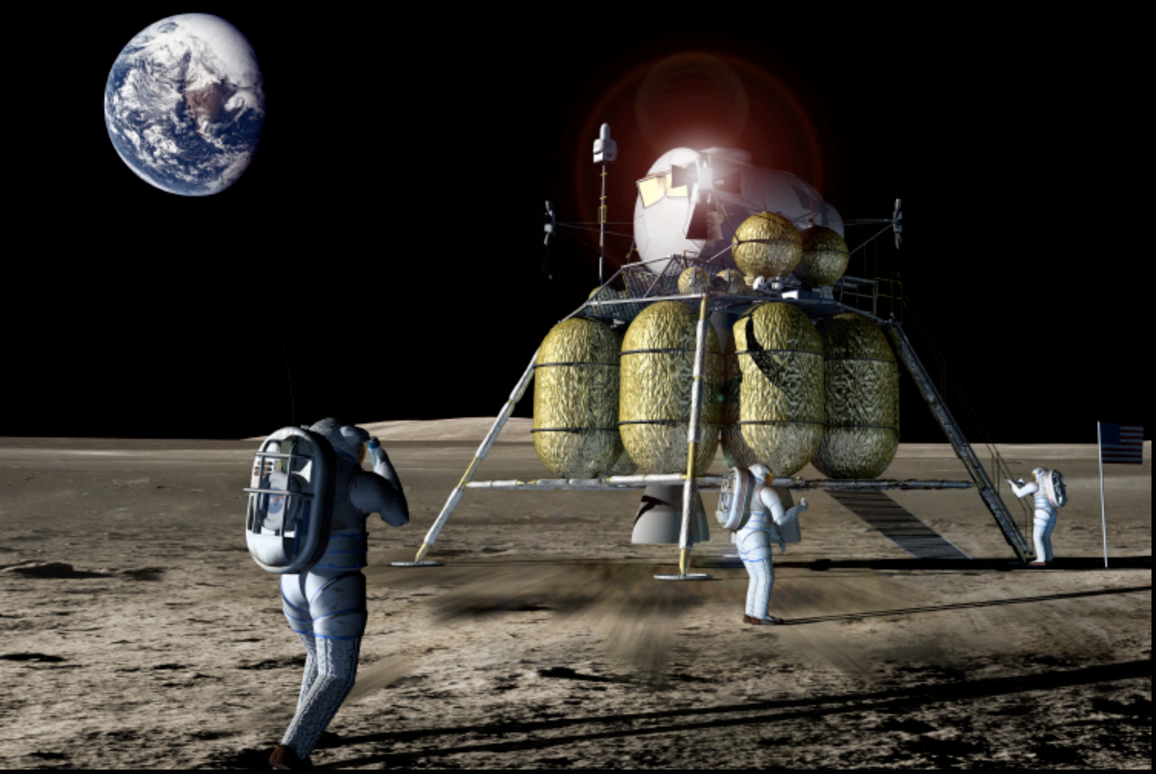
The Lunar Poles: An Ideal Site for Scientific Exploration?



Yes!

1. It's the Moon

2. The Poles Offer a Unique Exploration Opportunity

What Good is the Moon for Exploration?

- A natural laboratory of planetary processes and history and a platform to observe the universe

- A place to learn how to conduct planetary scientific exploration

- An opportunity to use emplaced infrastructure and resources